Abstract

Increasing levels of dissolved organic carbon (DOC) have been detected in the last decades in water bodies of the Northern hemisphere, and climate change might fuel this rising. For drinking water reservoirs located in peatland catchments, already subjected to elevated amounts of DOC that needs to be removed, this might pose a further problem. Scotland is predicted to face warmer temperatures and a change in rainfall patterns, which will result in more frequent and severe summer droughts and in heavier winter precipitation. These conditions are not ideal for peatlands, which may undergo a drastic reduction in area. Using two bioclimatic envelope models (Blanket bog Tree model and Lindsay Modified model) that project blanket bog distribution in Scotland in the 2050s, we extracted the area of blanket bog that is at risk of loss. Assuming that also part of the carbon stored in this area is likely to be lost, we calculated how much of it can end up every year as DOC in catchments that contain public drinking water reservoirs. This analysis is a first estimate of the risk for the provision of drinking water from peatlands in Scotland due to climate change. The aim is to identify the catchments that may face the highest consequences of future climates in terms of the concentration of DOC ([DOC]), where more sophisticated water treatments might be needed. Our results show a great variability among the catchments, with only few of them not affected by this problem and others that could experience substantial seasonal increase in [DOC]. This highlights the necessity to frequently monitor DOC levels in the reservoirs located in catchments where the major problems could arise, and to take the necessary measure to reduce it. Given that peatland condition and vegetation cover play a fundamental role in influencing DOC losses, this study also offers an indication of where peatland restoration might be useful to counteract the projected DOC increase and bring the highest benefits in terms of safe drinking water provision.

1 Introduction

Peatlands are the result of thousands of years of accumulation of layers of organic matter, made possible by the particular climatic and environmental conditions that make plant degradation slower than the accumulation of dead plant material (Sjörs, 1980). In temperate regions, cold temperatures and abundant rains mean that the soil is waterlogged and the oxygen is scarce, so that aerobic decomposition is very low, allowing peat layers to build up. Although in the world peatlands cover less than 3% of the land (Xu et al., 2018), in Scotland they represent about 23% of the land territory (Bruneau and Johnson, 2014). Peatlands provide many important ecosystem services, the key ones being climate regulation, biodiversity conservation, water regulation and sense of place (Bonn et al., 2010).

In Scotland, as in many other parts of the northern hemisphere, peatlands are under threat because of climate change and degradation (Clark et al., 2010; Artz et al., 2014). Warmer temperatures and changes in the precipitation patterns, with an increase in winter rainfall, a decrease in summer rainfall, and an increase in extreme events with longer drought periods, have been predicted for the UK and for Scotland (Jenkins et al., 2009; Werritty & Sugden, 2012). Under these conditions, peatlands are subject to stress and can lose their ability to accumulate peat and start releasing the carbon that has been trapped for millennia (Heathwaite et al., 1993). When peatlands sequester carbon, they are defined “active” (Bruneau & Johnson, 2011). In these peatlands, more carbon is sequestered and accumulated in peat layers than is emitted by plant respiration in the form of CO_2 or by methanogenic archaea in the form of CH_4, or lost in the water in the form of dissolved organic carbon (DOC), dissolved inorganic carbon (DIC) and particulate organic carbon (POC). If water table height is reduced or if peat vegetation is lost, leaving bare peat exposed, peatlands are likely to lose the carbon sequestration function. Furthermore, the carbon stock that has been accumulated when they were functioning, is at risk of being lost.

Scottish peatlands are estimated to store around 3000 Mt of carbon (Rees et al., 2018), 1883 Mt in the first 2 meters according to Aitkenhead & Coul (2020). If even some of this carbon was released, this would represent a problem not only for CO_2 emissions, but also for the DOC that will likely end up in water bodies. It has been estimated that around 10-20% of carbon losses from peatlands are represented by DOC (Limpens et al., 2008). An excessive amount of DOC in freshwater bodies may present a problem if this water is used for drinking purposes. DOC itself is not dangerous but it has an impact on colour (making water brownish) and reacts with disinfectants used in water treatment plants, creating disinfectant by-products (DBPs) that are considered harmful for human health (Valdivia-Garcia et al., 2016; Davies & Mazumder, 2003). In particular, the formation of one type of these DBPs, the trihalomethanes (THMs), that occurs when chlorine reacts with organic compounds present in water, increases in the presence of high [DOC] (van Leeuwen et al., 2004; Valdivia-Garcia et al., 2016; Valdivia-Garcia et al., 2019). However, this is not the only factor, and DOC composition also plays an important role in this process (Gough et al., 2014). Irrespectively, THMs have been recognised as carcinogenic compounds and the EU and the UK Government have imposed a limit of 100 $\mu g\ L^{-1}$ in drinking waters (EU, 1998). For these reasons, although there is not a legal limit of [DOC] in drinking waters, when its level is too high, other treatments are necessary before disinfection in order to reduce it. The EU drinking water regulations only specify that for total organic carbon (TOC) there must not be “abnormal changes” (EU, 2014), while French regulations add a limit of 2 $mg\ L^{-1}$ for TOC in treated waters intended for human consumption. In particular, Levi (2004) and Ratnayaka et al. (2009) suggest that for a [DOC] > 4 $mg\ L^{-1}$, it would be difficult to maintain [THMs] below the threshold of 100 $\mu g\ L^{-1}$ for a contact time of 2-3 days with chlorine. According to the province of Saskatchewan (Canada), raw water can easily be treated if [DOC] remains below 2 $mg\ L^{-1}$, while for concentrations over 5 $mg\ L^{-1}$, water treatment becomes much more complicated, with the possibility of exceeding [THMs] and a dramatic increase of costs

(Government of Saskatchewan, 2009). The Irish EPA suggested that with [TOC] greater than 4 mg L^{-1}, water treatment works will likely have to add extra treatments, while if [TOC] is between 2 and 4 mg L^{-1} the situation needs to be monitored and studied to understand if it could lead to an excess of THMs (EPA, 2010). The excess of [DOC] has lately been flagged as one of the major problems for drinking water quality around the world, and an increase of [DOC] in streams and lakes of the Northern hemisphere has been detected in the last decades (Filella & Murillo, 2014; Skjelkvåle et al., 2001; Skjelkvåle et al., 2005), not only in peatland habitats. Some examples come from studies conducted in the UK (Evans et al., 2006), North America (Meyer-Jacob, 2019), Norway (Hongve et al., 2004), Sweden (Erlandsson et al., 2010), Czech Republic (Oulehle & Hruška, 2009) and Germany (Musolff et al., 2017). [DOC] is predicted to further increase with increasing temperatures (Salimi & Scholz, 2021), drought periods (Riston et al., 2017, Lee et al., 2021) and CO_2 levels (Hejzlan et al., 2002, Fenner et al., 2021). However, climatic variables have not been the only cause of the recent increase, and a diminishing of anthropogenic sulphate depositions has also substantially contributed to it (Monteith et al., 2007).

The raise of [DOC] has been identified as one of the major water treatment costs for drinking water suppliers in Scotland (Murray et al., 2020). DOC can be removed through coagulation, whose efficiency depends on many factors related to the raw water that enters the treatment plant, such as pH, temperature, [DOC] and turbidity, but also on the type (aluminium or iron salts) and dose of coagulant and the mixing time (van Leeuwen et al., 2004, Gough et al., 2014). This method is the most used by water companies because it is the best compromise between removal efficiency and costs. In Scotland, over the 90% of all the potable water is supplied by water treatment works that use coagulation, which can remove 70-90% of the DOC (Murray, 2020). High [DOC] in raw water though, leads to higher coagulant requirements, disinfectant demand, sludge production and decreased filter duration, which will inevitably increase the operational costs (Riston et al., 2014;

Eikebrokk, 2004). Besides this, in order to control the formation of THMs, other steps may be needed, like pre-ozonation, micro and nanofiltration and enhanced coagulation, which require major operational investments. For example, the US Environmental Protection Agency has estimated that adding granular activated carbon (GAC) filtration would increase the treatment costs by 15% on average (Cashman et al., 2014). Overall, therefore, release of DOC into water is likely to increase the complexity and cost of water treatment, and this is a particularly important challenge in catchments containing substantial proportion of peatland.

Around 70% of drinking water in Scotland and in the UK comes from catchments that encompass peatland areas (van der Wal et al., 2011), where, due to the presence of large amounts of organic matter, [DOC] is already much higher than in catchments situated on mineral soils (Hope et al., 1997). This water is supplied to 28.3 million people in the UK, over 43% of the population (Xu et al., 2018). With climate change posing a threat to the peatlands carbon store, significant amounts of carbon have the potential to be released into water bodies, decreasing the quality of drinking water, increasing costs, and posing a risk for water security. It is important therefore to develop an understanding of where this risk is greatest, both in terms of the volume of water and likely number of people affected.

In this study, we used the results of bioclimatic models applied to Scottish blanket bogs (a particular type of peatland that in Scotland represents 92% of the total peatlands area – Clark et al., 2010) from Ferretto et al. (2019), to explore how much carbon is at risk of being released as DOC in water bodies by the 2050s from this habitat. The final aim is to understand to what extent this may represent a problem for drinking water quality and where the impacts will be the highest. In spite of the importance of this issue for the future availability of drinking water and its relative cost, to our knowledge only three studies have attempted to model the future [DOC] in UK peat-fed water supplies (Lee et a., 2021; Xu et al., 2020; Naden et al., 2010). This is the first study that looks at all the Scottish Water reservoirs in peatlands, giving an initial country-wide assessment of the location of areas where drinking water provision is at high risk from DOC release.

2 Methods

From Ferretto et al. (2019) we obtained the area of blanket bog that is considered at risk because of climate change according to two different bioclimatic envelope models (the Blanket Bog Tree Model (BT) and Lindsay Modified Model (LM)). These projections represent the modelled distribution of blanket bog in Scotland in the 2050s, according to two different emission scenarios (low and high). The two models provide two different projections, based on different combinations of variables (BT is based on the balance between evaporation and precipitation, which regulates the level of the water table and LM is based on temperature and precipitation - see equations 1 and 2, which have originally been developed by Clarke et al., 2010).

$$\text{Probability of Blanket Peat} = 1 \text{ if } T_{max} < 17.4°\text{C } \textit{and} \text{ TMI} > 0.41$$
$$\textit{or}$$
$$T_{max} > 17.4°\text{C } \textit{and} \text{ AAMWD} < -28.6 \text{ mm} \qquad \textbf{(1)}$$

where

T_{max} = maximum yearly temperature

TMI = Thornthwaite–Mather Moisture Index (which is a measure of the annual balance between precipitation and potential evapotranspiration)

AAMWD = annual accumulated monthly water deficit (which, in contrast to TMI, accounts for the seasonality in the balance between precipitation and potential evapotranspiration).

$$\text{Probability of Blanket Peat} = 1 \text{ if } P > 1000 \text{ mm and } T_m < 15°\text{C} \qquad \textbf{(2)}$$

where

P = total yearly precipitation

Tm = maximum monthly mean temperature

Both the models forecast a decrease in blanket bog distribution in the 2050s, but while in the BT model the main retreat is in the East, in the South and in the Flow Country (in the Northeastern corner), in LM model the main retreat is in the East, around the Central Belt, and, only in the high emission scenario, in the South (see Supplementary Information, figures S1 and S2). Something that needs to be noted though, is that the two models fail to detect the blanket bog that is currently present in the easternmost portion of the Flow Country, adding some uncertainties on the future prediction in this area (Ferretto et al., 2019). The original projections have a resolution of 25 km and were then downscaled to 100 x 100 m to calculate the potential loss of carbon at a scale that is more relevant to for a catchment level. Koehler et al. (2011) measured the net ecosystem carbon balance (NECB) for an Atlantic blanket bog for a period of 6 years in Ireland, and registered the highest carbon loss in 2006, when the bog was a source of 8.6 g C $m^{-2.}$. We used this as a reference value to calculate the maximum amount of carbon that could be lost every year per unit area. This value is the photograph of the NECB of just one year in a particular location, but it was chosen because we wanted to constrain the amount of carbon that can be lost where the blanket bog is at risk (not all the carbon in areas defined “at risk” will be released in such a short timeframe), and at the same to have a realistic number that represents the carbon losses when the blanket bog acts as a source of carbon. In the study of Koehler et al. (2011), 2006 has been the year with the greatest interannual variation of precipitation, with the wettest autumn and the driest summer, which might resemble what is forecasted for Scotland in the near future (Jenkins et al., 2009). According to this value, the quantity of carbon that could be released amounts to 860000 g C ha^{-2} per year, and we applied it to every 100 x 100 m pixel. To check if in every pixel there is enough carbon to support the assumption of a constant loss at this rate, from the same NECB value, we first calculated the depth of peat that could be lost in 30 years, assuming a value of bulk density of 0.088 g cm^{-3} - as estimated by Ratcliffe et al. (2018) for Scottish peatlands - and assuming that carbon represents 50% of the peat organic matter.

But not all the carbon at risk of loss will be released in the rivers as DOC. We assumed that a quantity that spans from 10 to 20% of the total carbon at risk will be lost as DOC, so we tested these two levels. This range was chosen according to the values found in the literature: Holden (2005) and Limpens (2008) stated that DOC losses are typically around 10% of the total carbon losses and Worrall et al. (2009) measured the carbon budget of a catchment in northern England over 13 years, finding that DOC losses comprised around 15% of the total. From these studies and from expert opinion (Christopher Evans, personal communication), we selected the 10-20% range (i.e. of the yearly total carbon which is at risk of being lost according to our calculations, we considered that 10-20% is made up of DOC).

The values of DOC that are projected to end up into Scottish water bodies were then converted to DOC concentration in the water, by dividing the potential DOC stock by the yearly flow rate of the rivers. The total stock was first divided by 30 (years from 2021 to 2050) to get the mean yearly quantity of DOC (mgC yr^{-1}) at risk, and then divided by the yearly river flow (L yr^{-1}), to obtain the yearly increase of [DOC] (mgC L^{-1}).

A network of river monitoring stations is spread around the UK (Supplementary Information, figure S3). We downloaded the catchment boundaries from the River Flows Network website (https://nrfa.ceh.ac.uk/), and we assigned each catchment the value of the mean flow rate (m^3/sec) of the corresponding monitoring station, creating a 100 x 100 m raster (Supplementary Information, figure S4). Since the monitoring stations do not cover all the Scottish river catchments (see Supplementary Information, figure S3), for those areas not represented we obtained the values through an interpolation from the nearest pixels. This is certainly an important approximation, necessary because of the lack of data for some of the catchments. The areas not covered by the sampling network are, though, a small proportion of the total (that corresponds to the white areas in figure S3, Supplementary Information), and most of the catchments of high interest for this study are located in areas where data is available (of the 94 reservoirs analysed, 79 are in catchments with empirical data and 15 are in catchments with interpolated data, most of which are in the Islands and in the West Coast).

Finally, the flow rates were converted from $m^3 sec^{-1}$ to $L yr^{-1}$, to calculate the yearly [DOC] in $mg L^{-1}$. This [DOC] does not represent the total [DOC] in the water bodies, but the further amount of [DOC] that is projected to be added into the waters of the corresponding catchment because of the degradation of blanket bog caused by climate change, predicted by the BT and LM models.

Data of measured [DOC] were obtained from the Scottish Environmental Protection Agency (SEPA) for the period 2017-2019. This dataset contains the [DOC] measured in many stations located around Scotland, with a monthly frequency of measurement for most of the stations. We used these data as a baseline to provide a picture of the current situation. From each station, the median value of all the seasonal measurements was taken. Where in the same catchment there were multiple stations, the median values were averaged and a single value for each catchment was obtained. For some of the catchments the data were not available; in these cases, if the catchment was part of a bigger catchment with available data, these data were used; if also this option was not possible, the catchment was left without current [DOC] data.

From Scottish Water, we obtained the locations of the public drinking water reservoirs located in peatland areas (94), with indications of the number of people served (more or less than 100,000 or compensation reservoirs – i.e. reservoirs used to maintain a certain amount of downstream flow below an impounding reservoir). We focussed the study on the catchments where the reservoirs are located. We calculated the quantity of DOC that can be released in these catchments by blanket bog degradation, following BT and LM projections. Since [DOC] can be highly variable during the year, we analysed seasonal [DOC] values. Our future projections of DOC cannot be directly calculated season by season but are obtained from a stock of DOC that risks ending up in water bodies, from which we assumed that the same amount will be released every year. To calculate the projected seasonal addition of DOC, we assumed a ratio of 20:20:30:30 respectively for winter, spring, summer and autumn. This ratio was chosen observing the annual trends of [DOC] in the current data, and we assumed that this ratio is not going to change in the future. Other studies have reported a seasonal variation of [DOC], with the peak in autumn and the lowest values in winter and early spring (Pickard et al., 2017; Gough et al., 2014, Neal et al., 2005, Halliday et al., 2012).

Since the exact number of people served by each reservoir was unknown, we assigned an arbitrary value (5, 3 and 1) to each reservoir's category of the variable "people supplied" (>100,000, <100,000 and compensation reservoirs), to reflect the relative importance of each reservoir, in terms of people supplied. In this way we ranked the catchments, summing up the value of the reservoirs that lie within them and identifying the catchments that supply drinking water to the greatest number of people.

In total, we modelled the increase in [DOC] for 8 scenarios: two different blanket bog models (BT and LM), each one following two different emission scenarios (low, high), for two percentages of carbon lost as DOC (10% and 20%) and with 2050 as reference year (i.e. we used the projections from Ferretto et al. (2019), where the carbon at risk of loss is calculated for the 2050s).

We also showed the results in more detail for the catchments with the highest importance in terms of people served and for the catchments with the highest projected [DOC] increase.

3 Results

3.1 Drinking water hotspots

The current [DOC] and the projected addition of DOC was calculated for all the catchments where there is at least one drinking water reservoir. In figure 1 (and in table S1 in Supplementary Information) the catchments considered in the study are shown, together with their importance for the provision of drinking water. The scores obtained by all the catchments range from 1 to 25. Only two catchments have a score of 1, meaning that they only include one compensation reservoir. In all the other catchments, at least one reservoir that supplies less than 100,000 people is present. In the most important catchment (score = 25) located in the central belt, northeast of Stirling and part of the river Devon catchment, there are five reservoirs (Castlehill, Glenquey, Glensherup, and Glendevon upper and lower) each one of them supplying more than 100,000 people. The second catchment for importance (score = 17) is located in the south of Scotland, southeast of Glasgow, and is part of the river Clyde catchment; it includes one reservoir that supplies more than 100,000 people (Daer) and four reservoirs that supply less than 100,000 people (Cowgill lower and upper, Coulter and Camps). The third most important catchment (score = 15) is also located in the Central Belt, northwest of Stirling. To this catchment belong three reservoirs that supply more than 100,000 people (Glen Finglas, Loch Katrine and Loch Venachar).

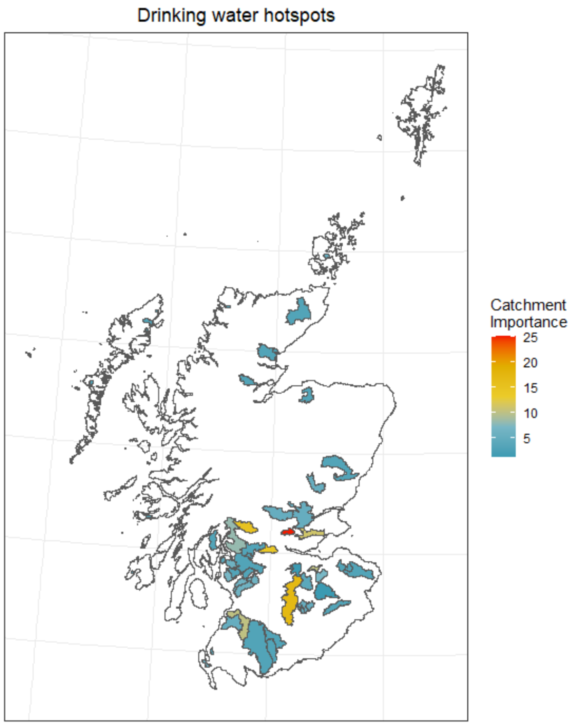

Figure 1 Catchments containing public drinking water reservoirs, ranked by their importance in terms of people supplied. Each reservoir was assigned an arbitrary score of 5, 3 or 1 if the reservoir supplies more than 100.000 people, less than 100.000 people or if it is a compensation reservoir, respectively. By summing the reservoirs scores within each catchment, we obtained the catchments' score.

3.2 Current [DOC]

The current [DOC] (2017-2019) is shown in figure S5 and in table S2 (Supplementary Information) for each season. In winter, the catchments had a value of [DOC] that spans from 2.06 mg L^{-1} to 14.4 mg L^{-1}, with a mean value of 5.59 mg L^{-1}. The mean spring value is similar (5.09 mg L^{-1}) and the range is 1.4 - 9.99 mg L^{-1}. In summer and autumn, the range is much wider: 2.08 – 36.4 mg L^{-1} in summer and 2.9 – 25.25 mg L^{-1} in autumn, with a mean of 7.19 mg L^{-1} and 7.77 mg L^{-1} respectively. The catchments with the highest [DOC] are the catchment with Loch Calder in winter, spring and autumn, and the catchment with Craigendunton reservoir in summer. The catchments with the lowest [DOC] are the catchment with Loch Assapol in winter, the catchment with Cowgill reservoir (lower and upper), Coulter reservoir, Camps reservoir and Daer reservoir in spring and summer, and the catchment with Afton reservoir in autumn. The percentage of catchments with [DOC] higher than the threshold of 4 mg L^{-1}, above which the formation of an excess of THMs is considered very likely (Levi, 2004; Ratnayaka et al., 2009) and particular treatments necessary, is 66% in winter, 68% in spring, 77% in summer and 86% in autumn.

3.3 Future projections

3.3.1 Overall trend

Future projections of extra DOC that could be released from the degradation of blanket bogs, as a consequence of climate change, were calculated for all the catchments with one or more drinking water reservoirs. Using the NECB value of 8.6 g C m^{-2} from Koehler et al. (2001) as a proxy of the carbon that can be lost yearly, a bulk density value of 88000 g m^{-3} (from Radcliffe et al., 2018), and assuming a carbon content of 50% (Koehler et al., 2011), the peat depth that could be lost in 30 years amounts to 5.85 mm. Since the minimum depth to define peatlands in Scotland is 50 cm, in each hectare where blanket bog has been identified there is enough carbon to allow the hypothetical loss of 86,0000 g C per year per 30 years.

Given the strong assumptions necessarily used to calculate the future [DOC] increase, the focus of this section is not on the numbers themselves but rather on the ranking of the catchments, with the aim to identify those with the highest risk of DOC increase. Therefore, we grouped the results into ranges of projected DOC increase per catchment (table S3, Supplementary Information). According to the BT model, low emission scenario, only in nine out of 60 catchments an increase in [DOC] is not predicted in any seasons (eight if we consider the high emission scenario), while for the LM model, the catchments not affected by projected [DOC] increase are 11 considering the low emission scenario or 12 considering the high emission scenario. The two classes with the highest predicted [DOC] increase are 4 – 8 mg L^{-1} per season per year, and over 8 mg L^{-1} per season per year. Considered together, they account for over one third of the catchments in summer and autumn, and around 25% of the catchments in winter and spring (with small changes according to the model and the scenario) (see table S3). The same results are shown in form of pictures in figures S6 and S7.

Of the 94 reservoirs, 23 supply more than 100,000 people and most of them are located in the Central Belt and in the south of Scotland, with only one big reservoir in the Orkney Islands. Of these, the only reservoir where none of the models predict an increase of DOC in their catchments is Fruid reservoir in Southern Scotland. The catchment with Loch Lomond (North West of Glasgow, in the West coast) is not predicted to increase its yearly [DOC] when the BT distribution is used, while with the LM distribution it is predicted to increase its yearly [DOC] in the range 0 – 10 mg L^{-1}. The projections for the catchment with Loch of Kirbister, in the Orkney islands, do not forecast an increase of [DOC] if the BT low or the LM low and high emission scenarios distributions are used, but forecast an increase of [DOC] per year in the range 20 – 40 mg L^{-} with the BT high distribution.

Finally, for the catchments with Megget reservoir and the catchment with Talla reservoir, both in the South of Scotland, only using the LM low distribution, an increase of [DOC] is not forecasted, while using the other blanket bog projected distributions, the predictions are of an increase of [DOC] per year in the range 20 – 40 mg L^{-} for the catchment with Megget reservoir, and 0 – 10 mg L^{-} for the catchment with Talla reservoir. All the other big reservoirs are predicted, according to all scenarios of both of the blanket bog distributions, to suffer a yearly increase of DOC in their catchments in the ranges 0 – 10 mg L^{-}, 10 – 20 mg L^{-} or 20 – 40 mg L^{-}, but none of them over 40 mg L^{-} (figure 2). These ranges were obtained according to the subsequent assumptions that were made with respect to the loss of climatic space projected by BT and LM models, and assuming that DOC represents the 10% of the total carbon at risk of loss (for the assumption of 20% of carbon lost as DOC, see table S4 in the Appendices).

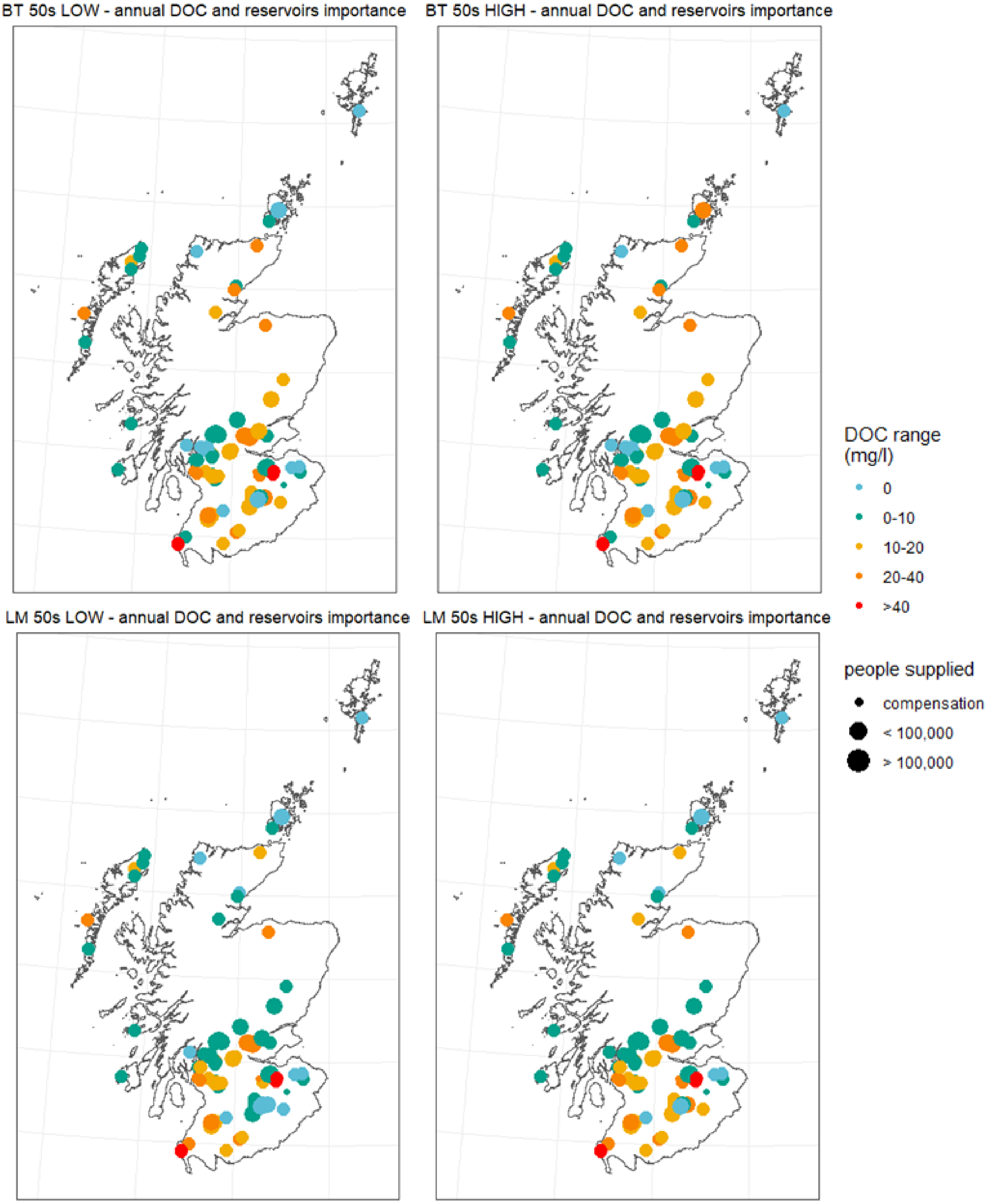

Figure 2 Scottish Water reservoirs displayed according to their importance in terms of people supplied (size of the dots) and in terms of projected yearly DOC increase in their catchments (colour of the dots) using the BT and LM distributions (low and high emission scenarios), assuming that 10% of the total carbon at risk of loss is lost as DOC.

The catchments that we have identified as critical, either because they are hotspot of drinking water or because the highest seasonal increase of [DOC] is predicted, are illustrated in figure 3.

The catchment that includes Glendevon (lower and upper), Glensherup, Castlehill and Glenquey reservoirs, has the highest importance (score = 25) considering the number of people served. According to the future projections, both BT and LM models suggest a yearly amount of extra DOC in the catchment in the range 4 – 8 mg L^{-} in winter and spring and of over 8 mg L^{-} in summer and autumn. The second catchment for importance (score = 17) includes Cowgill (Lower and Upper), Coulter, Camps reservoirs and Daer reservoir. The projected extra DOC obtained with the BT model is in the range 2 – 4 mg L^{-} in winter and spring and 4 – 8 mg L^{-} in summer and autumn, while using the LM modelled distribution, the projected increase is between 0 and 2 mg L^{-} in any season according to the low emission scenario, and in the range 2 – 4 mg L^{-} in winter and spring and 4 – 8 mg L^{-} in summer and autumn according to the high emission scenario.

The third important catchment (score = 15) includes Glen Finglas, Loch Katrine and Loch Venachar reservoirs. According to both the scenarios of the BT model, the [DOC] could increase in any season of 2 – 4 mg L^{-1} , while according to both the scenarios of LM model, the increase could be in the range 2 – 4 mg L^{-1} in summer and autumn, but only 0 – 2 mg L^{-1} in winter and spring.

Coming to the catchments with the risk of the highest seasonal [DOC] increase, for two catchments, using both the LM and the BT distribution and considering any scenario, the projected increase is of over 8 mg L^{-1} in any seasons. These catchments have a score of 6 and 7, including two reservoirs that supply over 100,000 people (Dindinnie and Knockquhassen) the first, which is located in the South-westernmost corner of Scotland, and two reservoirs that supply over 100,000 (Rosebery and Gladhouse) people plus a compensation reservoir (Edgelaw) the second, which is located South of Edinburgh.

The catchment with the Glenlatterach reservoir (score = 3), South of Elgin, is projected to increase its [DOC] of over 8 mg L^{-1} using any blanket bog distribution but only in summer and autumn, while in winter and spring the projected increase is in the range 4 – 8 mg L^{-1}.

Only according to LM model, the catchment with Penwhirn reservoir is predicted to increase its [DOC] of over 8 mg L^{-1} in summer and autumn and of 4 – 8 mg L^{-1} in winter and spring, while for the BT model, the increase is much lower (in the class 0 – 2 mg L^{-1} for any scenario and in any season).

Finally, the catchment with Loch Calder (score = 3), in the Flow Country, is projected to increase its [DOC] of over 8 mg L^{-1} in summer and autumn and of around 4 – 8 mg L^{-1} in winter and spring using the BT distribution, while the range is 4 – 8 mg L^{-1} in summer and autumn and 2 – 4 mg L^{-1} in winter and spring using the LM distribution.

Figure 3 Location of the catchments included in a deeper analysis (the zoomed images are not in scale) (Copyright OpenStreetMap contributors)

4 Discussion

The aim of this study was to assess if the carbon predicted to be at risk in blanket bogs, as a consequence of climate change, can represent a threat for drinking water provision in Scotland. The results rely on some relatively substantial generalisations and assumptions (which we discuss in detail, below) and are not meant to give a detailed and accurate picture for each catchment. They are rather intended to identify where the major problems could arise, both in terms of quantity of DOC that could be released and in terms of number of people affected. This study focuses on Scotland, but the same approach could be adopted in other countries where DOC increase is becoming a pressing issue for drinking water providers. A preliminary national scale assessment could in fact help addressing efforts and resources where there is more need.

4.1 Uncertainties and assumptions

Our study focuses on blanket bogs, leaving out other types of peatlands that could also make up an important source of carbon losses in the context of climate change. However, blanket bogs represent over 90% of peatlands in Scotland and over 94% in the catchments considered in this study. Besides this, blanket bogs are the type of peatland that mostly relies on climatic conditions, because they are fed only by rainfall (in contrast to minerotrophic peatlands like fens that are also fed by groundwater) and will hence suffer most by climate change. For these reasons, we think that our projections are robust from this point of view and that the major bulk of carbon losses from peatlands are accounted for. Another uncertainty linked to the choice of the blanket bog layer is that its current distribution (used to train the model in Ferretto et al., 2019) is not the result of just the climatic conditions, but also of the land use change that has occurred in the past. For this reason, some areas could be still climatically suitable for blanket bogs, even if blanket bogs are not currently present. Although this could be an issue in Scotland, where great areas of blanket bogs have historically been converted to other uses, the coarse resolution (5x5 km) of the model has limited the problem: in fact, even if in the 5x5 km cell there is only a small fraction of blanket bog, the entire cell has been considered as climatically suitable (Ferretto et al., 2019).

We tested two levels of DOC loss – 10% and 20% of total carbon loss. Higher rates of DOC loss (43% of the total carbon loss) have been reported at some sites (Worrall et al., 2011a; Billet et al., 2010), so it is possible that DOC losses could be even higher than those estimated here, but the 10-20% range for DOC loss is thought to be more typical (Holden 2005; Limpens et al., 2008; Worrall et al., 2009). In particular, the figure of 43% refers to a bare peatland site. Since vegetation cover influences the export of fluvial components of the carbon cycle (DOC and POC), one of the first thing to look at when going into detail, is to assess the status of the blanket bog cover and the type of vegetation within the catchment considered. Munir et al. (2015) found that the loss of carbon (in terms of CO_2) from a warmed blanket bog that had been drained 10 years earlier, were much lower than the loss of carbon from a warmed blanket bog whose water table had recently been lowered. This indicates that the past land use is also an important factor to be considered when accounting for the carbon emissions. In particular, the interactions between temperature and water table can lead to different outcomes on the basis of the blanket bog history. In the 20th century in Scotland, peatlands have been drained for agricultural purposes, afforested with non-native species for timber, overgrazed, burned for grouse hunting, and cut for fuel (Bruneau & Johnson, 2014), so that over 80% of their area is to some extent damaged. This past management could influence their future reaction to climate change in terms of DOC losses.

Another important simplification in this study is made with regards to the amount of carbon at risk by 2050. We considered that in the whole area where blanket bogs are predicted to be at risk of loss, the fixed amount of 8.6 g C m $^{-2}$ will be released every year. This value represents the NECB for an Atlantic blanket bog, measured by Koehler et al. (2011), in the year 2006. This is only a single measure of a particular year in a particular site, while in reality many different factors can influence the NECB of a blanket bog, leading to different results. We hence took this value to constrain the maximum loss of carbon from the peat depth where the blanket bog is considered at risk because of climate change, but this is only one of many possible realistic values.

We also considered that all the DOC predicted to be at risk, will be released at the same rate every year. In reality, the rate of DOC loss can vary according to many factors that are not included in our study. In particular, a dry period followed by a heavy rainfall has the capability to mobilize a large amount of DOC in a single event (Clark et al., 2007; Grayson & Holden, 2012, Tang et al., 2012) and this is what usually happens with the so called "autumn flush": the first autumn significant rainfall, flushes away the organic matter broken down by the microbial activity in summer, which in turn is enabled by the summer's lower water table and warmer temperature (Mitchell & McDonald, 1992). This means that our results show the mean annual [DOC] increase as a proportion of the total carbon stock at risk every year up to 2050, but high fluctuations are likely to happen, especially considering that climate models forecast an increase of summer droughts and extreme rainfall events in Scotland (Jenkins et al., 2009; Werritty & Sugden, 2012).

To calculate the increase of [DOC] from the stock of DOC at risk, we used the gauged daily flow data from the National River Flow Archive, which represents the daily mean of the water flow in the measurement stations, from the first measures taken - which depend on the station - up to 2019. It is important to consider, though, that the mean water flow varies with stream order and climate and might change in the future. Xu et al. (2020), modelled future flow in nine UK peatland catchments and found a reduction of the mean discharge (-27% to -2.9%, with a mean of – 12.1% in the 2030s and -40.1 to -2.8% with a mean of -15.6% in the 2090s). A negative relationship has been found between discharge and [DOC] in peatlands, caused by dilution of DOC (Grand-Clement et al., 2014, Clark et al., 2008). With a reduction in the flow, the [DOC] might be higher than predicted.

The last assumption made is about the seasonality of DOC losses. According to the current data on seasonal [DOC] measured in the catchments, we estimated that the loss of DOC is divided between the seasons with a ratio of 20:20:30:30 in winter, spring, summer and autumn respectively. It is important to consider, though, that this percentage is related to the current climatic conditions and that with an increase of drought periods in summer and rainfalls in autumn, this ratio is likely to change in the future. Some studies have already reported that the highest future increase of [DOC] in the UK and in western Europe is predicted in autumn and in winter, when more rainfall will lead to more flushing (Xu et al., 2020; Naden et al., 2010).

4.2 Future projections of [DOC] and future [THMs]

Despite all of the above caveats, our results give some useful information on the potential risk that Scottish drinking water reservoirs might face in the near future. Drinking water companies around the world are already taking steps to tackle a generalized increase of [DOC], because the problem has long been known. Increase of [DOC] has been in fact observed in many sites of Europe and North America (Filella & Murillo, 2014; Skjelkvåle et al., 2001; Skjelkvåle et al., 2005).

4.2.1 Causes of increased and increasing [DOC] and the role of climate change

Many explanations have been provided for the widespread rising trend of [DOC] in the waters of the northern hemisphere. One of the most cited causes is the decline of anthropogenic sulphur depositions (Monteith et al., 2007), and recently it has also been investigated the role of the decline of nitrogen depositions (Musolff et al., 2017). But climatic factors have played their role too, and are acquiring more importance as the effect of the decline of acidic depositions is slowing down (Marty et al., 2021). Meyer-Jacob et al. (2019) have shown that the decline in acid deposition has been the main driver of increasing [DOC] in lakes that had been subjected to high acid deposition at the beginning of the 20th century, masking the role of climate. But in areas where the acid deposition was low, the influence of climate change has caused a gradual increase of [DOC] over the preindustrial background levels (1850s). Also Evans et al. (2006), observing a 91% increase in DOC across 22 UK upland waters over 15 years, in the 1990s and early 2000s, indicated the decline of anthropogenic sulphur emission and deposition as the main cause, but suggested that increases in temperature could also explain 10 – 20% of this rise. Another important influence on [DOC] is represented by droughts, which are predicted to increase their frequency and their magnitude in the future. Ryder et al. (2014) measured daily [DOC] in an Irish catchment mostly covered by peat and found that [DOC] reached its minimum during a drought event, to then increase significantly with the first high rainfall and stayed high for months, till another step change occurred. At this point, the [DOC] decreased significantly, but remained higher than the pre-drought value. Lee et al. (2021) also found that the combined effects of droughts and acidic deposition will lead to a substantial increase in [DOC] in two peatland catchments in Wales in the near future, in particular in late summer and autumn. The mechanism that guides the [DOC] increase after a drought could be explained by the enzyme latch mechanism suggested by Freeman et al. (2001). Besides leading to an increase in the amount of DOC, droughts have also been found to decrease DOC treatability in peatland catchments (Riston et al., 2017).

In light of the increase in temperature, summer droughts and extreme events predicted for Scotland and the decrease of climatically suitable areas for blanket bogs, the first estimate of [DOC] increase in Scottish reservoirs provided by our study, points out the seriousness of the challenge and identifies the areas where a more detailed assessment should be carried out. According to our results, in fact, many catchments could face a substantial increase in [DOC], making it very challenging to reduce concentrations to a point where THM formation will not exceed the legal limits in treated waters. Some of our projections return a DOC increase that is exceptionally high. A yearly increase of [DOC] in the range 20 - 40 mg L^{-1} in an area that supplies over 500,000 people, as in the case of the catchment that hosts Glensherup, Castlehill, Glenquey and Glendevon (lower and upper) reservoirs, must be interpreted in the light of the uncertainties listed above, but it tells us the potential risk that the drinking water from this catchment faces if all the carbon at risk, stored in the area, is released.

4.2.2 Relationship between [DOC] and [THMs]

The relationship between [DOC] and [THMs] is complex, and [DOC] is not the only factor affecting THMs formation. There are several studies that have explored the mechanisms that lead to the formation of THMs. Davies & Mazumden (2003) reported that [THMs] in treated water depends on temperature, chlorine demand, total organic carbon concentration and contact time. Valdivia-Garcia et al. (2016) analysed 93 water treatment plants in Scotland to identify the predictors of THM concentration in final potable waters and in distribution networks, finding that DOC, chloride and most of all ambient temperature are related to THMs formation. An interesting finding is also that temperature is related to THMs in those treatment plants that use chlorination, while there is not this relationship in treatment plants that use chloramination, while Goslan et al. (2009) found a higher [THMs] in water treatment works in Scotland that use chlorination (median = 106 $\mu g\ L^{-1}$) compared to those that use chloramination (median = 48 $\mu g\ L^{-1}$). Lu et al. (2009) analysed THMs trends at different [DOC] using chlorination and chloramination and found not only higher values of THMs for chlorination, but also that the rate of THMs formation increased much more during chlorination than chloramination at increasing [DOC] (from 2 mg L^{-1} to 8 mg L^{-1}). Given the increasing [DOC] and temperature forecasted in Scotland, switching chlorination with chloramination could be one of the possible solutions to lower THMs formation. Kristiana et al. (2009) also found much less THMs formation with chloramination *vs* chlorination processes, but they also detected a proportionally higher concentration of non-THM DBPs, for which health risk is unknown.

Although not the only one, DOC concentration is a key parameter for THMs formation during disinfection, and it is crucial for water treatment plants to keep monitoring it. In this study we found that in some catchments, the amount of DOC potentially added every year to each catchment could, alone, be greater than the current measured [DOC]. Combining this information with the projected increase of temperature, this could create major challenges for some water treatment plants. Valdivia-Garcia et al., (2016) found that a 500% annual increase in [DOC] from a baseline of 1.7 mg L^{-1} would increase [THMs] by 352%, while Valdivia-Garcia et al. (2019), for the same percentage of DOC increase (from 1 mg L^{-1} to 5 mg L^{-1}), found an increase of 315± 18% at the fixed temperature of 15˚ C during chlorine disinfection. In most of the Scottish catchments, the current [DOC] is already over the suggested limit of 4 mg L^{-1} to avoid a [THM] that exceed the legal limit of 100 μg L^{-1}, especially during the summer and autumn seasons. Our study has shown that around half of the catchment considered, could experience yearly increases of [DOC] of at least 2 – 4 mg L^{-1} per season, and also catchments that have current [DOC] lower than 4 mg L^{-1} could soon exceed this threshold. For example, one of the most important catchments in terms of people supplied, which contains the reservoirs of Cowgill (Lower and Upper), Coulter, Camps and Dear, currently exceeds the 4 mg L^{-1} limit only in autumn (4.95 mg L^{-1}), but in most of our scenarios it is predicted to increase its [DOC] of 4 – 8 mg L^{-1} in summer and autumn and of 2 – 4 mg L^{-1} in winter and spring. This would make it really likely to exceed the 4 mg L^{-1} thresholds in any season, making then necessary extra treatments and increasing the costs for the water company.

4.2.3 Our projections compared with other studies

Although many studies have investigated the impact of DOC on THM formation, less studies have modelled future [DOC] in peatlands and its impact on drinking water at wide scale. Few mesocosm studies have investigated the effects of predicted climate change on [DOC] in peatlands (Fenner et al. 2021 in Wales; Salimi et al., 2021 in Sweden). Both these experiments have shown a significant increase of [DOC] under future climate conditions, although in Salimi et al., this is true only for the worst Representative Concentration Pathway scenario (RCP 8.5). Naden et al. (2010) modelled the impact of climate change on DOC in some European lakes and they found that in two Irish lakes with 70% and 43% of peat cover in the relative catchments, DOC could increase by 20% and 65% respectively in the period 2071-2100. Most of the increase is forecasted in late autumn and early winter**.** Their model is based on the production of DOC by a decomposition rate of organic matter regulated by temperature and soil moisture, and DOC washout through different hydrological pathways. DOC production is assumed to be independent of the carbon stock, which is not considered a limiting factor. Delpla et al. (2015) modelled future [DOC] in Quebec as a result of climate change and used the output as input for modelling future [THMs]. They used an ensemble of empirical models to link climate variables (temperature and rainfall) to water temperature and [DOC]. According to their study, by 2050s and 2080s, DOC is predicted to increase, especially in autumn and winter, and to slightly decrease in summer. This study is not directly comparable with our results, because it does not specifically look at peatland habitat and because in Quebec, from December to March, the ice cover slows down DOC transportation. Nonetheless, the same approach could be used in Scotland to further investigate the DOC increase in the catchments that we have considered.

Xu et al. (2020) used a dynamic process-based model (Integrated Catchments model for Carbon - INCA-C - from Futter et al., 2007) to project future DOC concentration and flux under climate change and sulphate deposition change in drinking water reservoirs in UK peatland. They found that [DOC] is predicted to increase by 14.8% across all catchments and future scenarios in the 2030s (26.5% in the 2090s). They also found a more pronounced seasonal variability of [DOC] (autumn and winter the seasons with the major increase), which they attributed to the increasing seasonality of precipitation and temperature, while the decrease in sulphate deposition is thought to be the driver of the overall change in mean annual [DOC]. Their suggestion for handling this increase in [DOC] is to focus on peatland restoration, to make them more resilient to climate change and to limit erosion, but also to improve water treatments, especially in autumn and winter. Since we expressed the results in ranges, it is not possible to calculate the exact change in percentage from the current values in our study, but taking the middle value of the range, the average yearly [DOC] increment is around 33% (using the mean of the median seasonal values), but there are strong differences among the catchments, with some of them reaching a seasonal increase of over 100%. Our model is much simpler than that of Xu et al. (2020), but it covers all the Scottish Water reservoirs on peatland areas. One way forward could be to apply the model developed by Xu et al. (2020) to those areas that in our study show the highest risks, both in terms of extremely high DOC levels and in terms of risk for the high number of people supplied. The large differences between DOC projections in some of our catchments and the results of Xu et al. (2020) are partially due to the fact that we did not model the loss of DOC directly, but we derived it assuming that a fixed amount will be released every year from areas that are no longer predicted to be climatically favourable for blanket bogs. It is unlikely that every year the blanket bogs at risk will be a net source of carbon, but our aim is to stress on the possible risk that lies beneath some of the catchments that are predicted to experience climatic conditions that are outside the bioclimatic envelope for blanket bogs. The same INCA-C model used in Xu et al. (2020) has also been adopted to estimate the future [DOC] in two Welsh catchments by Lee et al. (2021), with the addition of equations that include the enzymatic latch process explained by Freeman et al. (2001). They also found an increase of [DOC] in the near future (2020–2049) - which is predicted to stabilize in the far future (2070–2099)- which is mainly attributable to increasing drought periods.

4.3 Implications for water security in Scotland

The main aim of this study was to identify the location of the major criticalities for drinking water availability that could arise as a consequence of bog degradation due to climate change in Scotland, and to assess if this may constitute a problem for future drinking water security. From our results, in terms of concern about the amount of DOC that is predicted to end up in water bodies, substantial variability among the catchments is evident, with only a few showing no likely changes and others that are predicted to face a great risk. We suggest the results of our study should be used as a starting point for a better and more detailed assessment of those catchments that – because of their importance for drinking water availability and/or the risk of the substantial DOC increases that they face - may need to be carefully monitored and studied. In particular, we have identified some hotspots of drinking water, most of them in the Central Belt, where about 70% of the Scottish population is concentrated. But some smaller reservoirs also need to be monitored because of the high amount of DOC that could be released from their catchments (for example Loch Calder, Penwhirn, Dindinnie, Knockquhassen, Rosebery, Gladhouse and Glenlatterach reservoirs).

Finally, consideration needs to be given to some reservoirs that, although smaller, are the only source of public drinking water in some remote areas, and are predicted to undergo a high increase of DOC in their catchments. This includes, for example, almost all the reservoirs in the Outer Hebrides, Glenlatterach reservoir in the Northeast and Loch Calder in the North coast. Coastal and island reservoirs are currently threatened by the high level of brominated THMs, that can be formed also at low levels of DOC (Murray, 2020). In these areas, the efficacy of treatments that remove DOC has a crucial importance, even more so given the predicted DOC increase. Scottish Water has already started reinforcing the monitoring of DOC in their reservoirs, with the installation of online DOC sensors, and using treatments like enhanced coagulation, granular activated carbon filtration or ion exchange in some water treatment plants (Valdivia-Garcia et al., 2019). In parallel with these technical investments, as Xu et al. (2020) already suggested, the cheapest and most effective way to act is through peatland restoration, particularly to preserve and/or re-establish blanket bog vegetation. However, the outcome of these activities in UK peatlands is mixed. Some studies have registered a lowering of DOC levels after the revegetation of damaged peat (Worral et al., 2011b) or after gully blocking combined with revegetation (Maskill et al., 2015). Riston et al. (2016) instead, looked at the treatability of DOC formed in sites with a different vegetation cover, finding that where there is a dominance of *Sphagnum* species, the DOC produced is easier to treat and remove compared to the DOC produced in presence of vascular plants. On the other hand, other restoration activities have, in the short term, led to an increase of DOC (Qassim et al., 2015) or produced no difference (Alderson et al., 2019). A comprehensive review can be found in Williamson et al. (2020), who conclude that restoration can increase the resilience of the system, bringing positive effects to the water sector, but alone it is not enough. Tools to monitor and predict the future DOC, are needed to make each intervention (whether it deals with the management of the catchment or it is an infrastructural operation) more targeted and well-timed.

5 Conclusions

Many studies have shown that the trend of DOC is projected to increase under future climates, especially in catchments that are partially or entirely on peatlands. Our study also shows a predicted increase of [DOC] in almost all Scottish water bodies in the future, assuming that a certain amount of carbon will be lost every year by those blanket bogs that will be outside their climate envelope. We examined Scotland as a whole and we considered all the reservoirs that supply public drinking water, which to some extent are within peatlands. Our study could help selecting the peatland areas that need high protection and investments in order to maintain high quality drinking water. In the densely inhabited Central Belt, some of the catchments which provide the majority of the drinking water to the local population, could face a seasonal [DOC] increase that alone would exceed the [DOC] threshold to avoid an excess of THMs. Other reservoirs in more remote catchments, like Loch Calder or Penwhirn reservoir, are predicted to suffer the highest seasonal DOC increase (over 8 mg L^{-1} in summer and autumn). Despite being smaller, they are the main source of drinking water in those areas. In all these reservoirs, more adjustments in water treatment works may be required and peatland restoration should be addressed in order to supply safe drinking water in the future. Being a first estimate that relies on many assumptions, a further and more detailed study in those reservoirs that may have the worst consequences is also required.

Authorship

A.F., R.B., P.S. and R.M. conceived the study, A.F. wrote the manuscript and conducted the analysis. All the authors helped to write and reviewed the final version of the manuscript.

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