The role of peatlands in global and regional drinking water resources

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Copyright Declaration

Assertion of moral rights

This thesis is dedicated to the memory of my late grandmother

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Abstract

Water provision is a valuable ecosystem service that is of central importance to human well-being. Peatlands are potentially important to the sustainable provision of potable water because water draining from peatlands is often of good quality, other than being rich in dissolved organic carbon (DOC). However, there have been no attempts to date, to investigate the role of peatlands in potable water supply at a global scale. In this thesis, an improved global peatland map (PEATMAP) was developed, which is freely available as a potentially useful tool for peatland or wetland researchers. The new map provided a basis from which to estimate global hotspots of peatland-derived potable water use. The volume of annual drinking water delivered by these catchments was estimated, and the status of the water-supply peatlands were evaluated, being the first such estimates at the global scale. Application of PERSiST and INCA-C models across the nine catchments in the UK, which are among the most important peatland-derived drinking water supply catchments in the world, provided evidence of the potential changes in DOC concentration and DOC flux under 21st-century climate and sulphate deposition scenarios. The results show that total global peatland area is 4.23 million km^2, approximately 2.84 % of the world land area. Water supply peatlands provide approximately 4.22 km^3 yr^{-1} of peat-fed drinking water globally, equivalent to typical consumption of 71.4 million people, but only 28 % of water-supply peatlands are pristine or protected globally. Although DOC flux is largely insensitive to future climate change scenarios, DOC concentrations in UK water sources are likely to increase while discharges are likely to decrease under all 21st-century climate and sulphate deposition scenarios tested.

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List of Abbreviations

FAM – Flow Accumulation

GHG – Greenhouse Gas

GIEMS – Global Inundation Extent from Multi-Satellites
GIS – Geographic Information System
GLC – Global Land Cover
GLWD – Global Lakes and Wetlands Database
GPWv4 – Gridded Population of the World Version 4

GRanD – Global Reservoir and Dam database

GVF – Goodness of Variance Fit

HER – Hydrologically Effective Rainfall

HPWMC – Hybrid Palustrine Wetland Map of China

HWSD – Harmonized World Soil Database

HydroSHEDS – Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales

IMCG-GPD – International Mire Conservation Group Global Peatland Database

INCA-C – Integrated Catchments Model for Carbon

IPCC – Intergovernmental Panel on Climate Change

ISLSCP – International Satellite Land Surface Climatology Project

LCM – Land Cover Map

MAUP – Modifiable Areal Unit Problem

MC – Monte Carlo

ML d^{-1} – Million Litres per day

N-S – Nash-Sutcliffe

PDC – Potentially dissolved carbon

PERSiST – Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport

PPI – Peat Population Index

PRI – Peat Reservoir Index

RCPs – Representative Concentration Pathways

SDAM – Squared Deviations from the Array Mean

SDBC – Squared Deviations Between Classes

SDCM – Squared Deviations from the Class Means

SMD – Soil Moisture Deficit

SOC – Soil Organic Carbon

UKCP – United Kingdom Climate Projection

Chapter 1
Introduction

1.1 Background

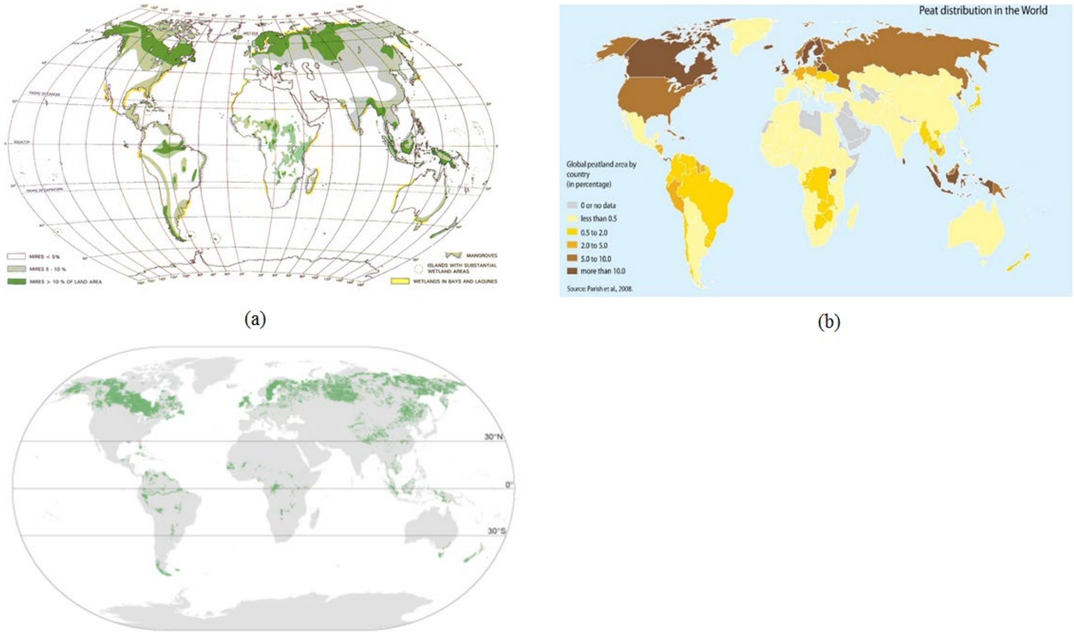
Normally, peat is regarded as the remains of partially decayed organic matter which has accumulated over time in waterlogged conditions, forming a land-based organic deposit. A peatland is defined as ‘an area with an accumulated peat layer at the surface of greater than 40-50 cm thickness’ (Charman, 2002; Rydin and Jeglum, 2013). Globally, peatlands are thought to cover around 3 % of the global total land area (Rockström et al., 2012) and represent at least a third of global wetland area (Parish et al., 2008). Though estimates vary depending on methods, it is estimated that peatlands store between a sixth and a third of all global soil carbon (Gorham, 1991; Limpens et al., 2008; Page et al., 2011; Yu, 2012). Peatlands have been claimed to deliver nationally and internationally valuable human-benefited ecosystem services, including regulating services, such as climate regulation and natural hazard regulation (Currey et al., 2011; Holden, 2005; Yu et al., 2010), provisioning services including water supply, agricultural production and sources of energy (Joosten and Clarke, 2002; Safford and Maltby, 1998), as well as supporting services and cultural services (Bonn et al., 2016). Of these ecosystem services, water provision is an often-stated example. Peatlands are potentially important to the global sustainable provision of potable water and drinking water security because water draining from peatlands is often of good quality, other than being rich in dissolved organic carbon (DOC). The literature often suggests that peatlands play important roles in water resource use (Grundling et al., 1998; Lee and Chai, 1996; Ong and Yogeswaran, 1991; Page and Rieley, 1998), and the streams or rivers that have flowed from peatlands may contribute to agricultural water, industrial water and domestic water (Barthelmes et al., 2012; Osaki, 2016; UNESCO, 2003). However, while the above papers make these statements, they do not actually demonstrate how important peatlands are for global water resources. There are similar unsubstantiated statements made at a local level. For example, many papers claim that approximately 70 % of Britain's drinking water comes from upland areas which are dominated by peatlands (e.g. Martin-Ortega et al., 2014; Stimson et al., 2017; Van der Wal et al., 2011), but this figure has never been verified and was in fact mainly based on a study of the Tees catchment (Grayson et al., 2012; Watts et al., 2001). Overall there is little quantitative evidence to show how important peatlands are globally for potable water resources and water security despite their potentially large water storage role.

Water security is a global concern and water demand and water resource imbalances in one region can affect other regions through water conflicts and migration, and trade. For example, water stress is the most often associated with conflict, migration in Cyprus and Israel and West Bank and Gaza (Selby and Hoffmann, 2012) and the virtual water trade has become a supplement to ensure water security in water scarce region (Antonelli et al., 2015; D'Odorico et al., 2019; Zhao et al., 2019). There are also concerns about global climate change and how this may affect the stability of peatlands and the implications for water quality and quantity from peat-fed water sources (Evans et al., 1999; Li et al., 2017; Pastor et al., 2003). A predicted warmer global climate could cause deeper peat water tables leading to peat compression (Whittington and Price, 2006) and reduced baseflows (Evans et al., 1999; Katimon et al., 2013; Whitfield et al., 2009). Deeper water tables may stimulate microbial decomposition of peat that can enhance DOC production (Fenner and Freeman, 2011). Also, a warmer and drier climate may enhance the risk of fires in many peatlands (Turetsky et al., 2015; Konecny et al., 2016; Worrall et al., 2006), which could further threaten water quality. Thus a global assessment is required to understand where the main water resource stress points might be related to peatlands under pressure from environmental change. This will help us understand whether there are any global risks to water security or whether the risks are more localised, and may also help provide underpinning support for further peatland protection and restoration.

The following sections provide a brief overview of some of the relevant background literature as a context for the study.

1.2 Global peatland mapping

Over recent years global peatland maps have been produced that are based upon aggregating the inventories of peat areas and remote sensing data at the national and local level (e.g. Figure 1.1). These inventories include shapefile, raster digital format data, and the histosols layer from the Harmonized World Soil Database or digitized paper sources. Also, remote sensing techniques are being developed for delineating potential peatland areas (Krankina et al., 2008), but they are not yet able to distinguish peatlands consistently. In any case, the quality of remote sensing data-derived land maps is required to be tested by validation against higher quality reference data (Congalton and Green, 2008; Zhao et al., 2014). Normally, *in situ* reference samples will often be necessary to validate remote sensing data through ground truthing, particularly for newly discovered ecosystems. However, validating peatland maps at the global scale based on *in situ* reference samples is a significant challenge. The other method for validating global peatland mapping based on remote sensing data may use proxy ground truthing points from legacy soil maps (e.g. Barthelmes et al., 2015) or knowledge-based interactive verification (e.g. Chen et al., 2015). However, a complete map using these methods is not expected until at least 2020 (Barthelmes et al., 2015).



(a)

(b)

(c)

Figure 1.1 Example peatland maps commonly cited in the literature: (a) peatland distribution expressed as a proportion of the land surface for different parts of the world, based on Gore (1983) and Vörösmarty et al. (2013). This map provides a general idea of where peatlands are an important part of landscapes and are based on incomplete data; (b) percentage area covered with peatland per country based on Parish et al. (2008). This map provides a general idea of countries with extensive peatland area; (c) global peatland map produced by Yu et al. (2010) which is until now the most up-to-date and highest resolution map.

Yu et al. (2010) produced one of these global maps and noted that accurate peatland coverage and distribution is not available for many regions. Their map is an estimated binary map. This binary map does not provide quantitative information in some regions. For example, the source data of Canadian peatlands only provides the percentage peatland cover in each grid cell rather than the shape files of peatlands. According to Figure 1.1 (a), showing the binary map presence in vector format, almost half of Canada is covered by peatlands, which does not correspond to the actual situation

(Tarnocai et al., 2011). In addition, peatlands in some regions (e.g. Southeast Asia, Patagonia, Australia) were manually digitized from other published figures on ArcGIS by Yu et al. (2010). Other available existing raster digital format global peatland maps have been derived from the global lakes and wetlands database (GLWD) (Grundling et al., 1998) and International Satellite Land Surface Climatology Project - Initiative I (ISLSCP I) dataset (Salvador et al., 2014) or Global Inundation Extent from Multi-Satellites (GIEMS) initiative (Vörösmarty et al., 2015), which are mainly based on remote sensing data and hydrological characteristics associated with soil databases. However, these current wetland mapping products generally do not have similar outputs (Melton et al., 2013). For example, Rockström et al. (2014) mapped the peatland distribution in the UK according to the Scottish definition of 'peaty soil' - 'peat soils' and 'organo-mineral soils' (Figure 1.2a), which is widely accepted by the national agencies (Biancalani and Avagyan, 2014; Davidson, 2014; Moxey and Moran, 2014). Figure 1.2b for the UK is extracted from Global Wetlands 1993 (UNEP-WCMC, 1993), which provides the global distribution and area of marsh, swamp, bog, fen, mire, and forest or flooded forest, marshland soil data extracted from remote sensing data and soil databases in different countries. The peatlands in Wales appear to be missing in Figure 1.2b compared to Figure 1.2a, probably because of the underestimation of peatlands based on remote sensing data without ground truthing. In addition, Figure 1.2a obviously provides much more detail than Figure 1.2b, which suggests the higher spatial resolution of the data source, the better the quality of the product. The peat distribution in Europe (Figure 1.2c) has been derived from the 1: 1 million European Soil Database (ESDB), using histosols data as a proxy for possible peat areas (Montanarella et al., 2006).

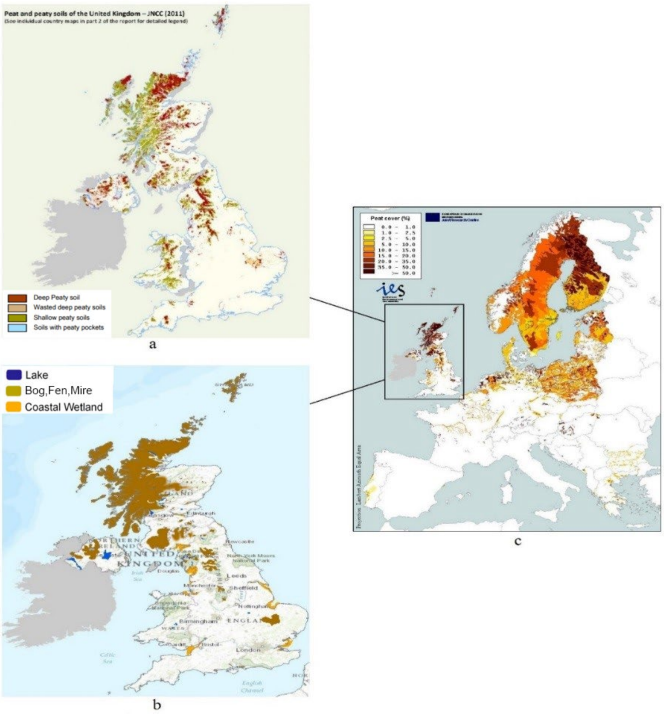


Figure 1.2 Peatland distribution in the UK according to different databases: a) peatland distribution produced by JNCC based on the Scottish definition of 'peat soils' and 'organo-mineral soils'; b) peatland distribution produced by UNEP-WCMC (1993) extracted from remote sensing data and soil databases; c) peatland distribution in Europe derived from the 1: 1 million European Soil Database.

Overall, the difficulties of peatland mapping at the global scale can be attributable to (i) ambiguous or non-uniform definitions of peatlands between different agencies; (ii) difficult environmental conditions for field surveys in some areas (e.g. uninhabited remote permafrost) to verify remote sensing data (Biancalani and Avagyan, 2014), and (iii) problems with remote sensing data in correctly identifying peatlands (e.g. the areas covered by permafrost or forest). Existing global peatland maps (e.g. Figure 1.1) that have been used to inform global peatland research (Turetsky et al., 2015; Vörösmarty et al., 2015; Zhu et al., 2013) lack fine spatial resolution or the most up-to-date peatland extents (e.g. from recent discoveries such as the vast Congo peatlands by Dargie et al., 2017). Therefore, a refined global Geographic Information System (GIS) map which presents the most detailed and up-to-date data available for any given location from a variety of national and regional databases is needed as a foundation from which to then determine the role of peatlands in global water resource provision.

1.3 Contribution of peatlands to human water use

Peatlands are reported to be important in providing water for human use both in areas where peatlands dominate the catchment landscape (e.g. UK uplands), and in regions (e.g. KwaZulu-Natal of South Africa and Sarawak of Malaysia) where isolated peatlands may provide a reliable year-round water resource (Grundling et al., 1998; Lee and Chai, 1996; Ong and Yogeswaran, 1991; Page and Rieley, 1998).

1.3.1 Potable water use

Because of the high cation exchange capacity and absorption qualities of peat, peatlands may filter out some contaminants and clean the water before it reaches the outflow from a site. Water draining from peatlands is potentially represents an important potable water resource for local people (Osaki and Tsuji, 2016; Silvius et al., 1984). When peatlands are located at relatively high altitude, they retain or discharge water in the upper basins, thus becoming important sources of water for local populations as well as people who live downstream (Miettinen et al., 1997; Pattinson et al., 1994). When peatlands are located at low altitude, they may catch flood waters or support low flows during dry periods. Peatlands located in the lower reaches of catchments associated with relatively flat topography can store water gradually in rainy seasons and then potentially provide water resources in the dry season, especially in freshwater-scarce coastal areas (Osaki and Tsuji, 2016).

Peatlands have been widely reported to be used as a potable water resource, in both the Northern and Southern Hemispheres (Table 1.1). For example, in the Northern Hemisphere, the Green Swamp, United States of America (USA), which although only about 345 m above sea level, can be regarded as relatively high altitude due to occupying a singular position at the top of the potentiometric high of the Floridan Aquifer System. It is located in the headwaters of the Palatkaha, Withlacoochee, Hillsborough, Alafia, Peace, and Kissimmee Rivers, providing water to local populations downstream (Marc, 2010). Another example is Lake Winnipeg, the largest lake in southern Canada, which is mainly surrounded by peatlands (many of these peatlands are mined) and provides drinking water resources to residents who live nearby (Du Moulin and Stottmeier, 1986). Gracz et al. (2015) indicated that peatlands within the Limpopo Creek Catchment which lies in the Cook Inlet Basin of Southcentral Alaska, USA play an important role in providing drinking water for local people during dry periods.

In the Southern Hemisphere, particularly in the tropical zones, peatlands are the main source of potable water during dry seasons. They play crucial roles in the supply of water for drinking, washing and irrigation in coastal villages (Hooijer, 2004; Silvius et al., 1984) such as in areas of Sarawak (Lee and Chai, 1996) and Sumatra, Indonesia (Claridge, 1991). In Papua New Guinea, swamp forests and grass or sedge fen-dominated peatlands are common in montane areas above 1000 m. Peat swamp forests are important water resources for downstream populations (Hope, 2014) when the seasonal water shortages due to the drought in the monsoon season. Many Peruvian High Andes peatlands are located along the margins of rivers and springs (e.g. peatland in the headwater area of Río Viscas at a 4200 m above sea level) providing domestic water to high-altitude human populations and downstream residents (Fonken, 2014; Schittek et al., 2015). In the temperate zone of the Southern Hemisphere, such as the Maluti Mountains of Lesotho (with altitudes ranging from 1400 to 3500 m above sea level) peatlands may also play important roles in water provision. The catchment areas which are mostly occupied by peatlands occur at high altitudes in the Maluti Mountains are an important water source for downstream population, particular during the dry season (Grab, 2010; Matete and Hassan, 2005; Nel, 2009) because they receive the highest rainfall in Southern Africa.

Table 1.1 Examples of peatlands reported being used as a potable water resource.

Peatland lactation	References	Region
Peatlands near Lake Winnipeg, Canada	Du Moulin and Stottmeier (1986)	Northern Hemisphere
Green Swamp, USA	Marc (2010)	
Peatlands lying in Cook Inlet Basin, USA	Glass (1999)	
Upland peatlands in the UK	Watts et al. (2001)	
Swamp forests and fens, Papua New Guinea	Hope (2014)	Southern Hemisphere
Peruvian High Andes peatlands	Fonken (2014), Salvador et al. (2014), Schittek et al. (2015)	
Sarawak coastal peatlands and Sumatra swamp forests, Indonesia	Lee and Chai (1996), Claridge (1991)	
Peatlands in the Maluti Mountains of Lesotho	Matete and Hassan (2005), Nel (2009)	

1.3.2 Agricultural water use

Peatlands also can provide water resources for agriculture. These agricultural activities happen both on peatlands (e.g. paludiculture) and non-peatlands which are irrigated by water drained from peatlands.

(1) Agriculture on peatlands

Examples of peatland water being used for agriculture are shown in Table 1.2. Paludiculture is ‘a suite of land management techniques that cultivate biomass from wet and rewetted peatlands under conditions that maintain the peat body, facilitate peat accumulation and sustain the ecosystem services associated with natural peatlands’ (Wichtmann and Joosten, 2007). Biomass may include black alder, reed, cattail, sedges, berries, and reed canary grass planted on fens and peat moss planted on bogs. Paludiculture has been practiced in Germany (Burvall et al., 1998; Mortensen, 1998), Belarus (Wichtmann et al., 2014), and North America (Vaičekonytė et al., 2014). Barthelmes et al. (2012) estimated that the highest potential was in Europe and East Asia with degrading peatland areas of about 0.22 million km² (mainly Russia, Belarus, Finland, Germany, Sweden, Poland) and 0.2 million km² (mainly Indonesia, China, Malaysia, Mongolia), respectively with potential for paludiculture use.

Table 1.2 Examples of peatlands reported to be used for agricultural water supply.

Agriculture type	**Example**	**References**
Paludiculture	Reeds in Northern Germany, Belarus and North America	Mortensen (1998), Burvall et al. (1998), Wichtmann et al. (2014), Vaičekonytė et al. (2014)
	184 useful paludiculture plant species in Western Pomerania	Abel et al. (2013)
	Peat moss planted on bogs in Germany	Wichtmann et al. (2014)
Pasture for grazing	Peatlands in the Florida Everglades, USA	Andriesse (1988)
	Peatlands in Peruvian Puna provide water and the food for local breeding camelids	Fonken (2014), Salvador et al. (2014), Schittek et al. (2015)
	Peatlands in Waikato and the Hauraki Plains, New Zealand	Evans (1990)

Agriculture type	Example	References
	British upland drained to improve the vegetation for grazing and provide water and food for sheep and deer	Lindsay et al. (1988), Worrall and Clay (2012)
Arable farming	In many European countries (e.g. The Netherlands, Finland, Russia, Germany, Ireland and the UK)	Williams (1995), Holden et al. (2004), Sly (2003), Nitsch et al. (2012)
	Mega Rice Project in Central Kalimantan, Indonesia	Limin et al. (2000)
	Ploughed fens in the USA	Bart et al. (2016)
	Peatlands in northern Japan	Miyaji et al. (1995)

Other peatland agricultural activities such as pasture for grazing, rice plantations, and fruit trees need relatively shallow water tables (e.g. pasture, rice, vegetables, horticultural crops require the water table at least 40 cm depth, and fruit trees require the water table at least 60 cm depth). Nevertheless, these peatlands still tend to be drained to lower the water table. In addition, the establishment of trees on the peat soil for later timber harvesting also enhances water use from the peatland, potentially further lowering the water table (Paavilainen and Päivänen, 1995; de Jong et al., 2015).

(2) Agriculture on non-peatlands

Peatlands can be water resources that make contributions to irrigation of agriculture on nearby non-peatlands. As the main water resource of nearby agricultural lands, especially in tropical rural coastal areas, water withdrawal from peatlands has been reported to play an important role in irrigation (Hooijer, 2004; Osaki and Tsuji, 2016; Silvius et al., 1984). For example, the tropical Andes provide important water resources for downstream residents. Local people have traditionally used the peatlands in the valleys as water sources for irrigation of potato cropping (Benavides, 2014). Peatlands are also important water sources for the irrigation of grazing pastures, especially in drier areas (e.g. xerophytic puna) with strong seasonality. One of these is in the Lesotho highland region, where headwater peatlands provide water for the local grazing of sedge-grass (Grab and Linde, 2014); similarly in the southern Puna plateau, Peru (Canales, 1987).

1.3.3 Industrial water use

After agriculture, industry is the second largest user of water and accounts for approximately 22 % of global water consumption (UNESCO, 2003). There are no published reports on the contribution of peatlands to industrial water use, but it is possible that a large proportion of water used for energy, cooling, processes or chemical reactions, and products comes from water withdrawn from lakes, rivers or streams for which peatlands may have played a supply role. Many hydroelectric plants benefit from peatland dominated water or are located near peatlands. For example, Norway, which is covered by a large proportion of peatlands, has advanced hydropower systems that constitutes half of Europe's total energy storage capacity (Bakken et al., 2016). Robert-Bourassa Hydroelectric Generating Station, Canada is a hydroelectric power station on the La Grande River that is part of Hydro-Québec's James Bay Project in Canada; annual generation is near 26,500-Gigawatt Hour. The land cover of the La Grande River Catchment is characterized by a high proportion of peatlands (Tarnocai et al., 2011). A similar situation also occurs in the Lesotho Highlands Water Project (Nüsser, 2003), which generate hydro-electricity for Gauteng Province - one of the most densely populated industrial regions in South Africa (Quinlan, 1995).

1.4 Peatlands and dissolved organic carbon (DOC)

1.4.1 Dissolved organic carbon (DOC)

Dissolved organic carbon (DOC) is a complex mixture of low and high molecular weight compounds that originate from vegetation, litter, soil leachates, plant root exudates, and microbial enzymes and biomass (Guggenberger and Zech, 1994; Thurman, 2012). DOC is operationally defined as the fraction of total organic carbon that can pass through a 0.45 µm syringe filter (Roulet and Moore, 2006). DOC concentration is the units of DOC per unit volume. Aquatic DOC is mainly produced from the breakdown of plant and microbial material in catchment soils (Lennon, 2004). The aquatic DOC in peatland catchment is composed of humic substances and live plant roots in the peat (Freeman et al., 2004). The changes of climate and atmospheric acid deposition may be the factors increasing DOC concentration from peatlands in the past decades (de Wit et al., 2007; Eimers et al., 2007; Erlandsson et al., 2008; Evans et al., 2006; Freeman et al., 2004; Worrall and Burt, 2004). Not only does most DOC colour the water (Worrall et al., 2003), leading to low aesthetic quality, it may become potentially harmful when water is treated. Although DOC does not pose a health risk itself, when DOC is chlorinated, carcinogenic by-products (e.g. trihalomethanes) may be produced (Chow et al., 2003).

DOC flux is the rate of flow of DOC per unit area over time. As a vast pool of organic carbon, peatlands hold more than 600 gigatons of carbon (Yu, 2012). The increased export of DOC from peatlands would be an important component of the regional and even global carbon cycle (Holden, 2005; Limpens et al, 2008) because it can turn peatlands from net carbon sinks to net sources (Billett et al., 2004). DOC flux is derived by multiplying DOC concentration by discharge rate. However, the long-term DOC fluxes might be contradictory since there is a positive relationship between DOC concentration and discharge rate (Clark et al., 2007). Hence, it is predicted that DOC fluxes from peatland catchments would increase (Clair et al., 1999; Frey and Smith, 2005; Worrall and Burt, 2005) or decrease (Moore et al., 1998; Pastor et al., 2003), mainly because of the different precipitation scenarios being applied.

1.4.2 Factors affecting peatland DOC

DOC must be both solubilised by biological decomposition processes and mobilised during flushing by rain, or snow-melt events (Fraser et al., 2001; Holden, 2005). Biological processes governing DOC release from soil organic matter and hydrological processes affecting its subsequent transport show strong patterns of seasonality, being related to temperature, water table position, plant community and the chemistry of the peat (Evans et al., 2006). Thus, any factors which will affect DOC production or hydrology could potentially change the quantity of exported DOC.

There is no single mechanism which has provided a sufficient explanation for observed increases in DOC concentration. It is generally recognized that organic carbon solubility is mainly controlled by soil solution chemistry. The atmospheric deposition will affect the soil solution chemistry. The mobilization of metal cations in acid-sensitive soils is associated with a larger amount of acid deposition, which will decrease organic matter solubility (Monteith et al., 2007; Vanbreemen et al., 1984). Vertical and lateral DOC fluxes are mainly controlled by hydrology due to water availability and peat properties (Holden, 2005). DOC production and organic carbon mineralization are largely dependent on soil temperature and moisture. Since the rate of primary productivity (Freeman et al., 2004) and biological activity (Hongve et al., 2004) will be facilitated by the warmer and wetter soils, aquatic DOC concentrations are always associated with a warmer and wetter climate.

Therefore, several factors have been proposed to affect peatland DOC concentration, here I list the potential climatic, atmospheric and anthropogenic factors as follows: (1) climate change, including air temperature (Freeman et al., 2001), precipitation patterns (Hongve et al., 2004; Larsen et al., 2011) and occurrence of severe drought (Ritson et al., 2017; Worrall et al., 2006); (2) atmospheric deposition, including nitrogen enrichment (Bragazza et al., 2006; Evans et al., 2008; Sawicka et al., 2017) and decline diminishment (Evans et al., 2006); (3) Land management activities, including drainage, extraction, managed burning, agriculture and restoration (Clay et al., 2009; Holden et al., 2004; Wallage et al., 2006; Worrall and Burt, 2004).

1.4.2.1 Impact of climate change on peatland DOC

For DOC to enter drinking water supplies, it must first be transported from the soil to the stream. Hence the impact of climate change on organic carbon losses from soil result from a complex interaction between physical mechanisms (e.g. water movement) and biogeochemical mechanisms relating to temperature and water availability.

Temperature and drought control the balance between biological accumulation of soil organic matter and its decomposition (enabling subsequent losses by aqueous and gaseous pathways). *In-situ* soil DOC concentrations are increased by temperature and deeper water table as shown in laboratory experiments (Fenner and Freeman, 2011; Stutter et al., 2007). The increased aquatic DOC concentrations may remain elevated for years after droughts (Evans et al., 2005; Ritson et al., 2017; Scott et al., 1998; Watts et al., 2001; Worrall et al., 2006). These may be because the concentrations of phenols and their inhibitory effect on hydrolase enzymes will be increased due to the lower water table under drought conditions (Fenner and Freeman, 2011; Freeman et al., 2001).

1.4.2.2 Impact of atmospheric deposition on peatland DOC

Chemical factors such as pH and ionic strength may affect the solubility of DOC (Evans et al., 2006). Thus changes in deposition chemistry which affect the pH and ionic strength have been investigated and linked to DOC concentration dynamics in peatlands (Adamson et al., 2001; Scott et al., 1998; Kalbitz et al., 2000). In relation to the increase in peatland DOC concentrations, several studies have suggested that declining acidity and ionic strength effects are a contributory factor to the observed record of increased DOC concentration, while some laboratory experiments suggested that the reduced soil solution DOC is associated with increases in both acidity and ionic strength (Butler, 2009; Erlandsson et al., 2010; Hruška et al., 2009).

Sulphate deposition has been suggested as an important factor driving DOC export in peatlands. Since the 1970s, DOC has been shown to increase in conjunction with a decrease in sulphate deposition. For example, Evans et al. (2006) suggested the increases in soil and aquatic DOC concentrations may be caused the reductions in soil solution sulphate associated with decreasing sulphate deposition. Monteith et al. (2007) reported a similar situation of rising DOC along with a decline in anthropogenic sulphate deposition. In contrast, the increased sulphate deposition may decrease the DOC export from peatlands. Figure 1.3 shows the relationship between sulphate and DOC suppression in peat soil water under simulated drought. Long-term data from Moor House-Upper Teesdale National Nature Reserve in the UK, and laboratory experiments, suggested that raised sulphate concentrations strongly suppressed DOC mobilization from the peat (Chapman et al., 2005). This process not only affected short-term DOC dynamics during droughts (Clark et al., 2005), but also controlled DOC dynamics over longer timescales. These observations of DOC dynamics from peatlands have been attributed to the change of organic carbon solubility controlled by soil solution sulphate concentrations (de Wit et al., 2007; Evans et al., 1988; Hruška et al., 2009; Löfgren et al., 2009; Tipping and Hurley, 1988).

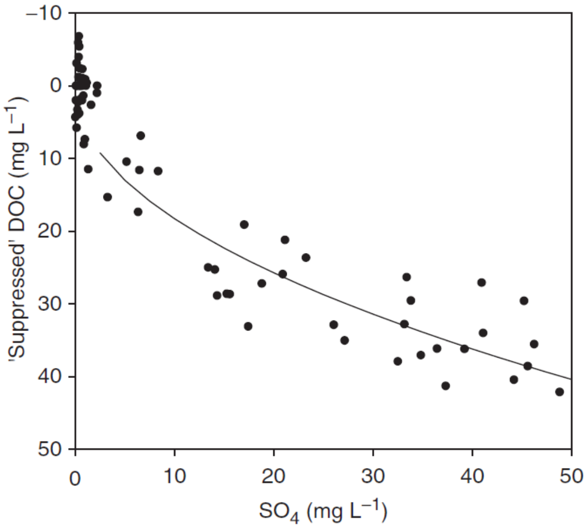


Figure 1.3 Relationship between sulphate and dissolved organic carbon (DOC) suppression in peat soil water under simulated drought. DOC and sulphate measured at 10 cm depth in peat cores at a controlled temperature of 10 ºC. DOC suppression is calculated as the reduction in concentration under drought conditions relative to expected concentrations at that temperature (Clark, 2005).

Compared to the relatively strong correlation between sulphur deposition and DOC concentration from peatlands, the effect of nitrogen deposition on peatland DOC is equivocal. Increased nitrogen concentrations (proxy to nitrogen deposition) has been observed to increase (Bragazza et al., 2006; Evans et al., 2008; Sawicka et al., 2017), decrease (de Wit et al., 2007; Michel et al., 2002), or have no net effect on (Emmett et al., 1998; Fernandez and Rustad, 1990; Worrall et al., 2006) DOC concentration.

1.4.2.3 Impact of land management activities on peatland DOC

The factors above could be enhanced by local land management (Wallage et al., 2006). Anthropogenic pressures such as drainage, extraction, managed burning and agriculture can lead to peatland degradation and impact peatland hydrology and aquatic DOC, while the peatland restoration may slow down or even reverse the degradation (Bonn et al., 2016). Artificial drainage is often associated with agricultural activities or peat extraction. By lowing water tables, increasing phenol oxidase, hydrolase activities and decomposition rates (Peacock et al., 2015), the potential for DOC retention within the soil decreases, thus the DOC in water in peatland catchments increases (Holden et al., 2004; Worrall and Burt, 2004). Kane et al. (2010) reported a 21.8 % increase in DOC when the water table was lowered in an Alaskan peatland over the course of four years. Strack et al. (2008) also documented an increase in DOC pore water concentrations in a peatland after 11 years of water table draw-down. Gibson et al. (2009) observed the DOC budgets in six peatland catchments (two were pristine; three where drains had been blocked; one unblocked drained) over two years and found higher concentrations of DOC in drained peatland than in the other five peatlands. Also, peatland extraction can alter aquatic DOC by changing peat properties, hydrology or vegetation. For example, Waddington et al. (2008) suggested that the cutover site exported more DOC in eastern Quebec in summer seasons. Other work in boreal peatlands or upland temperate systems also suggest there is increased leaching of DOC to surface waters in cutover peatlands (Laudon et al., 2009; Nieminen, 2003, 2004; Schelker et al., 2012). Furthermore, the effect of managed burning on aquatic DOC concentrations in peatlands has been subject to considerable debate (Davies et al., 2016; Marrs et al., 2019), and it mostly depends on the local site conditions. Some studies have shown increases (Grayson et al., 2012; Yallop et al., 2010; Yallop and Clutterbuck, 2009), some decreases (Savage, 2011; Worrall et al, 2007) and some no effect (Clay et al., 2009, 2010, 2012) except in the short-term period after burning.

In the modelling component of this thesis, I will focus solely on the atmospheric factors affecting peatland aquatic DOC because these happen across all peatlands, whereas management activities are relatively localised and site-specific.

1.5 Summary

Existing peatland maps, no matter whether they are at national or global scales, are rarely constructed using comparable definitions of peat or peatlands. Indeed, different specific research objectives may require different definitions. Other critical factors that limit global peatland mapping are the deficiencies of remote sensing data and lack of georeferenced information in some areas. Field mapping of peatlands is a considerable challenge, especially at global scales. Remote sensing provides an effective tool for extrapolating from field measurements to map peatlands over large areas, however, some peat (e.g. the areas covered by permafrost or forest) cannot be classified as peatlands by remote sensing data, and the interpretations of remote sensing data need to be validated with ground reference. Although there are the above limitations, a lot of work has already gone into improving regional and global peatland mapping. However, existing available global peatland maps are typically out of date, have a coarse spatial resolution, or are missing some important peatlands due to the quality of data source. Therefore, as a foundation to underpin global analyses of spatially-explicit interaction between peatlands, population and water supply systems (e.g. rivers and reservoirs), a high-fidelity, spatially accurate improved global peatland map is needed.

Peatland catchments located near high-density populations are potentially important to local human water use. Even small peatlands can be important for water regulation because they may store and release water that is later used for human activities. While local literature suggests that peatlands are important for water resources, there has not yet been a global assessment to determine exactly how much water is provided by peatlands and where the key water source peatlands are located. Of course, to undertake such an assessment there is a need for an adequate peatland map as a starting point.

Once drinking water resource supply peatlands have been identified it could be important to consider (by using predictive modelling, e.g. INCA-C) how changes in climate and atmospheric deposition chemistry may affect DOC because DOC removal is a costly part of the water treatment process. In peatlands the effects of temperature on the export of DOC concentration depend on interactions of soil warming (releasing the soil DOC via decomposition), seasonality in the relationship between temperature and decomposition (Fenner et al., 2005) and the quality and availability of the substrate for decomposition (Fang et al., 2005; Fang and Moncrieff, 2005). In addition, rainfall availability will affect the DOC by controlling water table and flows of DOC in rivers (Holden, 2005). The chemical factors including pH and ionic strength (Evans et al., 2006) could affect the solubility of DOC. Atmospheric deposition of sulphate can lower DOC concentrations by suppressing organic matter solubility (Monteith et al., 2007), and vice versa (Evans et al., 2006).

1.6 Research aims and objectives

The overall aim of this project is to investigate the role of peatlands in providing global and regional potable water resources and to understand the potential threat to key peatland-supplied water resources from future environmental change. To accomplish this aim, the following research objectives have been defined:

1) to produce an updated global peatland map with geospatial information for further spatial analysis;
2) to develop indices to estimate the quantity and hotspots of global peatland-derived potable water;
3) to select and apply a physically-based model to determine the water resource availability and DOC dynamics in waters draining from the most important peat-fed water supply catchments under climate change scenarios to the end of the 21st-century.

1.7 Thesis structure

In order to determine the role of peatlands in global potable water resource provision and whether there are key (hotspot) locations where large populations are highly reliant on peatland-derived potable water resources, it is necessary to determine the spatial distribution of peatlands and then determine how this relates to population distribution. To this end, a new global peatland map based on the most up-to-date information with high-resolution data has been developed. A peer-reviewed paper published in *Catena* with this new map is provided in Chapter 2, Appendix A and B. In Chapter 3 and Appendix C-E, a peer-reviewed paper published in *Nature Sustainability* is provided. In Chapter 3, the Peat Population Index (PPI) was developed to objectively quantify the global coincidence of human population and peatland cover at catchment scales. Another global index, the Peat Reservoir Index (PRI), which quantifies the catchment-scale contribution of peatlands to potable water abstraction from reservoirs, was also developed. These indices were used to estimate the quantity of global potable water that drains from or through peatlands. In Chapter 4 and Appendix F-G, the INCA-C model and PERSiST model were used to investigate changes of discharge and DOC concentrations and fluxes in peatland-derived water supply catchments under future climate and sulphate deposition change scenarios. The nine important peat-fed catchments in the UK were selected to be modelled, as Chapter 3 found the UK to be a global hotspot for peat-fed water supplies. The climatic drivers of the changes in river discharge and DOC dynamics in peat-fed catchments were analysed in Chapter 4. A synthesis of the work in this thesis is presented in Chapter 5 along with limitations and areas for further research.

1.8 Summary of methods

The overall approach involved mapping peatlands, populations and reservoirs to examine where water supply areas are supported by peatland contributions. Once the main areas were identified and peatland water supplies quantified, more concentrated regional modelling was conducted to examine how DOC concentrations and fluxes will change in the main areas to the end of the century.

An improved global peatland map was produced to provide the highest quality foundational dataset for determining the role of peatlands in global water resource provision. This map was formed by conducting a meta-analysis of geospatial information collated from the best available source data at various levels of scale. Here this project uses the criteria of relevance, spatial resolution and age to select the most appropriate data. The criterion of relevance requires that the data should be able to identify peatlands faithfully and to distinguish them from other land cover types. The criterion of resolution requires that the data should have a fine spatial resolution. The criterion of age requires the data should have been recently updated. Full details of the methods for developing the refined global peatland map are found in Chapter 2 and Appendix A.

There is not an available method to connect the global peatland extent, global population distribution and drinking water provision networks for quantifying global peatland water supplies. New methods to estimate the proportion of streams interacting with peatlands before draining into domestic water sources were produced and two new indexes-the Peat Population Index (PPI) and Peat Reservoir Index (PRI) were developed. To calculate the PPI and PRI, the global scale datasets of population, digital elevation model (DEM), river network, drainage direction and flow accumulation (FAM) data provided by Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner, 2013), and the Global Reservoir and Dam database (GRanD) (Lehner et al., 2011) were used combined with the new global peatland map. In addition, the Ecosystem-Land Use System (Nachtergaele and Petri, 2011) was overlapped onto identified global water-supply peatlands to determine the land-use on these drinking water supply peatlands. Full details of the methods of estimating the volume of potable water delivered by peatlands are provided in Chapter 3 and Appendix E.

DOC models will be needed to determine the future trajectory of DOC in drinking water catchments under future climate scenarios, and the INCA-C model was applied to generate projections. The required data for running INCA-C include daily precipitation and temperature, daily river discharge of outlets, land-cover and sulphate deposition data, and DOC concentration for the study catchments. It should be noted that there are extensive data required for operating INCA-C. The peatland catchments in the UK are unique in that they satisfy both of the following criteria: (1) play key roles in drinking water provision, and (2) all the required modelling data for INCA-C are freely available. Future climate scenarios were derived from the United Kingdom Climate Projection 2009 (UKCP09) (Jenkins, 2009) while future sulphate deposition dynamics were derived from the estimations from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) (Lamarque et al., 2013). More details of the methods of the projection of DOC dynamics in peatland-derived potable water under future climate change are explained in Chapter 4.

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Chapter 2
An improved global peatland map (Paper I)

Xu, J., Morris, P.J., Liu, J., Holden, J. 2018. PEATMAP: Refining estimates of global peatland distribution based on a meta-analysis. *Catena*. **160**, pp.134-140.

Abstract

Peatlands play important ecological, economic and cultural roles in human well-being. Although considered sensitive to climate change and anthropogenic pressures, the spatial extent of peatlands is poorly constrained. We report the development of an improved global peatland map, PEATMAP, based on a meta-analysis of geospatial information collated from a variety of sources at global, regional and national levels. This study estimates total global peatland area to be 4.23 million km^2, approximately 2.84% of the world land area. The results suggest that previous global peatland inventories are likely to underestimate peat extent in the tropics, and to overestimate it in parts of mid- and high-latitudes of the Northern Hemisphere. Global wetland and soil datasets are poorly suited to estimating peatland distribution. For instance, tropical peatland extents are overestimated by Global Lakes and Wetlands Database-Level 3 (GLWD-3) due to the lack of ground-truthing data; and underestimated using histosols to represent peatlands in the Harmonized World Soil Database (HWSD) v1.2, as large areas of swamp forest peat in the humid tropics are omitted. PEATMAP and its underlying data are freely available as a potentially useful tool for scientists and policy makers with interests in peatlands or wetlands. PEATMAP's data format and file structure are intended to allow it to be readily updated when previously undocumented peatlands are found and mapped, and when regional or national land-cover maps are updated and refined.

Keywords: Wetlands, Peat, Map, Geographic information system, Global, PEATMAP

Highlights:

- An amalgamated global peatland map with geospatial information is produced.
- Globally peatlands cover 4.23 million km^2, or 2.84 % of the global land area.
- PEATMAP includes recently identified high resolution peatland datasets.

2.1 Introduction

Peat consists primarily of plant detritus that has accumulated at the Earth's surface due to incomplete decomposition under close to water-saturated conditions. There is no single formal definition of ‘peat’ and ‘peatland’, with different interest groups often using their own definitions. For instance, Joosten and Clarke (2002) defined peat as ‘sedentarily accumulated material consisting of at least 30 % (dry mass) of dead organic material’, while Burton and Hodgson (1987) defined peat as ‘a soil with at least 50 % organic material, which is determined by measuring the ash left after burning’. In addition, histosols, which are regarded as peats in many regions, have been defined as ‘soils which either (1) contain at least 20 % organic material or (2) contains at least 18 % organic material if the soils have been saturated with water for 30 consecutive days’ according to the World Reference Base for soil resources (WRB) 2006 (Michéli et al., 2006). Peatlands have been defined as ‘an area, with or without vegetation, with a naturally accumulated peat layer at the surface’ (Joosten and Clarke, 2002). However, the minimum peat thickness for a site to be classified as a peatland is different depending on local classification schemes, country or even the scientific discipline, ranging from 10 cm to 100 cm (Bord na Móna, 1984; Joosten and Clarke, 2002; Mcmillan and Powell, 1999).

Peatlands represent significant stores of soil carbon and constitute an important component of the global carbon cycle (Page et al., 2011; Scharlemann et al., 2014; Yu, 2012). Pristine peatlands function as long-term carbon reservoirs because the rate of plant production generally exceeds the rate of organic matter decomposition (Frolking et al., 2011; Yu et al., 2011). Despite being large carbon stores, pristine peatlands can still emit sizeable quantities of methane and carbon dioxide, and are sources of water-soluble organic compounds with high interannual variability (e.g. Nilsson et al., 2008). However, peat degradation, which is promoted by climate change (Fenner and Freeman, 2011; Ise et al., 2008; Joosten et al., 2012), peatland drainage (Gibson et al., 2009; Holden et al., 2004; Joosten, 2009), burning (Clay et al., 2012; Page et al., 2002; Turetsky et al., 2015; Yallop and Clutterbuck, 2009) and conversion for agriculture (Carlson et al., 2013) can shift the balance of carbon fluxes so that peatlands become net sources of carbon compounds (Hooijer et al., 2012; van der Werf et al., 2008). Peatlands are not only carbon-dense landscapes but also play important roles in the provision of water resources and habitat. Peatlands provide a range of rare, threatened or declining habitats for plants and animals, and represent an important component of global biodiversity (Carroll et al., 2015; Posa et al., 2011). Peatlands contribute to human well-being by providing a range of other nationally and internationally valuable ecosystem services (Reed et al., 2014) including regulating services (e.g. flood regulation) (Gao et al., 2016; Holden, 2005), provisioning services (e.g. agricultural production, sources of energy, habitats for rare species) (Joosten and Clarke, 2002), and cultural services (Bonn et al., 2016).

Current estimates of global peatland cover contain large uncertainties, meaning that the capacities of peatlands to store soil carbon and to provide water and other ecosystem services remain poorly understood. Improving peatland mapping at regional and national scales represents an ongoing effort, and recent advances have been made in the forms of the Tropical and Sub-Tropical Wetland Distribution dataset (Gumbricht, 2015), the Irish National Soils Map (Teagasc, 2014), and refinements to maps of peatlands in the Central Congo Basin (Dargie et al., 2017). However, a high-fidelity, spatially accurate map of global peatland extent based on the best available data in each location is yet to be produced. Existing maps of global peatland extent are typically based on data that are out of date, of coarse spatial resolution, or based on studies from which the methods used to delineate peatlands are not available. For example, the widely cited map by Lappalainen (1996) gives peatland distribution expressed as a coarse proportion of land area at regional and continental scales. Parish et al. (2008) mapped proportional peatland cover by country, providing a national-level choropleth of peatland coverage without subnational detail. The more recent International Mire Conservation Group Global Peatland Database (IMCG-GPD) (Joosten, 2009) estimates were derived from a wide review of the available literature and from expert opinion, and are now widely used (Ciais et al., 2014; Davidson, 2014; Köchy et al., 2015; Smith et al., 2016; Urak et al., 2017). Joosten (2009), however, noted that IMCG-GPD contains large uncertainties, particularly in South America and Africa due to poor availability of source data there. At the time of writing the digital spatial dataset of IMCG-GPD has not been released in its entirety into the public domain.

The global distribution of peatlands might be estimated from maps of wetland distribution, which are common components of global land cover (GLC) products. Examples of widely used GLC datasets include ISLSCP II (Loveland et al., 2009), MODIS500 (Friedl et al., 2010) and UMD (Hansen et al., 2000), all of which are classified using the IGBP DISCover land cover classification system (Loveland et al., 2000); GLC250 (Wang et al., 2015); FROM-GLC30

(Yu et al., 2014); and GlobeLand30 (Chen et al., 2015). However, none of these GLC products identifies specific subtypes of wetland, meaning that peatlands cannot be distinguished from non-peat forming wetlands. Another potentially useful global wetland database is that of the Ramsar Sites Information Service (https://rsis.ramsar.org/). However, according to Article 2.1 of the Ramsar Convention (Ramsar Convention Secretariat, 2013), Ramsar sites classified as peatlands are likely to include large areas of adjacent non-peat-forming wetlands. Furthermore, only those wetlands which meet at least one of the ‘Criteria for Identifying Wetlands of International Importance’ can be designated by the appropriate national authority to be added to the Ramsar List. There are 596 Ramsar peatland sites globally, covering only approximately 0.5 million km^2. Ramsar data alone therefore represent only a small subset of the world's peatlands. The spatially-explicit, wetland datasets that specify peatlands as one or more subtypes (Table 2.1) are suitable for mapping peatland distribution. Among these datasets, GLWD-3 (Lehner and Döll, 2004) represents the most detailed, up-to-date wetland database from which global peat distribution might be successfully extracted (Köchy et al., 2015). Another method that has been used to map peatland distribution is to query soil databases for areas of organic-rich soils, such as the histosols (e.g. Köchy et al., 2015).

Table 2.1 Spatially-referenced inventories of global wetland distribution.

Reference or data product	Wetland categories	Spatial resolution	Date of most recent revision
Matthews and Fung (1987)	5 (forested bog, non-forested bog, forested swamp, non-forested swamp, alluvial formation)	1 arc-degree	1981
Aselmann and Crutzen (1989)	6 (bog, fen, swamp, marsh, floodplain, shallow lake)	2.5 arc-degree	1983
ISLSCP-I (NASA Goddard Space Flight Center et al., 1996)	6 (bogs, fens, swamps, marshes, floodplains, shallow lakes)	1 arc-degree	1988
GLWD-3 (Lehner and Döll, 2004)	12 (lake, reservoir, river, freshwater marsh, swamp forest, saline wetland, coastal wetland, bog/fen/mire, intermittent wetland, 50 %-100 % wetland, 25 %-50 % wetland, wetland complex)	30 arc-second	1992/1993

The aim of this study was to improve estimates of global peatland distribution compared to coarse, existing peatland maps and national choropleths, by amalgamating the most detailed and up-to-date data available for any given location from a variety of national and regional databases. In doing so, this study developed a new global GIS map of peatland distribution. Additionally, this study wished to make the new map and its spatially-explicit source data freely available for potential use by others; and to facilitate easy updates to the database in response to the exploration of previously unmapped peatlands (cf. Dargie et al., 2017) and other future refinements to national and regional data sources.

2.2 Methods

This study reviewed candidate data from a wide variety of sources that describe peatland distributions at global, regional and national levels. In areas of overlap between two or more datasets, this study determined that the best source data should: contain classifications that are of more direct relevance to peatland extents; possess a higher spatial resolution; and contain products that have been more recently updated in the candidate datasets. This study used the following sequence of comparisons to discriminate between overlapping data sources:

(1) Relevance. This study determined that the most important criterion was that source data are able to identify peatlands faithfully and to distinguish them from other land-cover types, especially non-peat-forming wetlands. For example, GIEMS-D15 (Fluet-Chouinarda et al., 2015) was rejected outright because it classifies wetlands into three levels of inundation, rather than distinguishing peatlands from other wetland types. Although GIEMS-D15 is a high-quality tool with valuable application to understanding wetland biodiversity, this study deemed it unsuitable due to its lack of direct relevance to peatlands.

(2) Spatial resolution. In areas where two or more overlapping data sources were indistinguishable in terms of their relevance to peatlands, we selected the dataset with the finest spatial resolution.

(3) Age. In any areas where two or more overlapping datasets were indistinguishable based on both their apparent relevance to peatlands and their spatial resolution, the data product that had been most recently updated has been selected. Recently updated products commonly contain much older

source data, but this study used the period over which the latest revision source data were collected as the primary measure of the age of a dataset.

A list of the best source data according to the above criteria is presented in Table A.1. Where source data overlapped the above criteria were applied to select the most appropriate data to use in PEATMAP in order of importance from 1 to 3 with 1 being most important. We combined these data sources to produce a new amalgamated global map of peatland distribution.

For areas where peatland-specific datasets were not available (i.e. Hokkaido, Mongolia and North Korea), this study estimated peatland extent based on the distribution of histosols derived from the Harmonized World Soil Database v1.2 (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012), in a manner similar to some previous studies (e.g. Köchy et al., 2015). HWSD is a raster database with a nominal resolution of 30 arc-seconds (corresponding approximately to 1 × 1 km at the equator) that contains soil data collected over more than 40 years. A map of histosols was derived from HWSD according to the FAO-74 and/or the FAO-90 soil classification. Overall, there are 15,494 km^2 of histosol cover in those areas where no other peatland-specific data are available (i.e. Hokkaido, Mongolia and North Korea).

2.3 Results and discussion

This new global peatland map, PEATMAP (Figure 2.1), estimates global peatland area as 4.23 million km^2, or approximately 2.84 % of the global land area. At a global scale, this estimate corresponds well with existing, oft-cited estimates of approximately 4 million km^2 (e.g. Parish et al., 2008).

Estimated peatland area in Asia accounts for 38.4 % of the total estimate of global peatland cover. North American peatlands comprise 31.6 %, followed by Europe (12.5 %), South America (11.5 %), Africa (4.4 %), and Australasia and Oceania (1.6 %). Estimated peatland area accounts for 5.42 % of the land area of North America, followed by Europe (5.2 %), Asia (3.6 %), South America (2.7 %), Australasia and Oceania (0.9 %), and Africa (0.6 %) (Table 2.2). The analysis of this study identifies the major peatland complexes in the circum-arctic zone, particularly the Western Siberian Lowlands in Russia, and the Hudson and James Bay Lowlands in Canada; as well as other important concentrations at lower latitudes, including extensive peat-dominated wetland or swamp forest landscapes such as the Congo and Amazon Basins, and those of Southeast Asia.

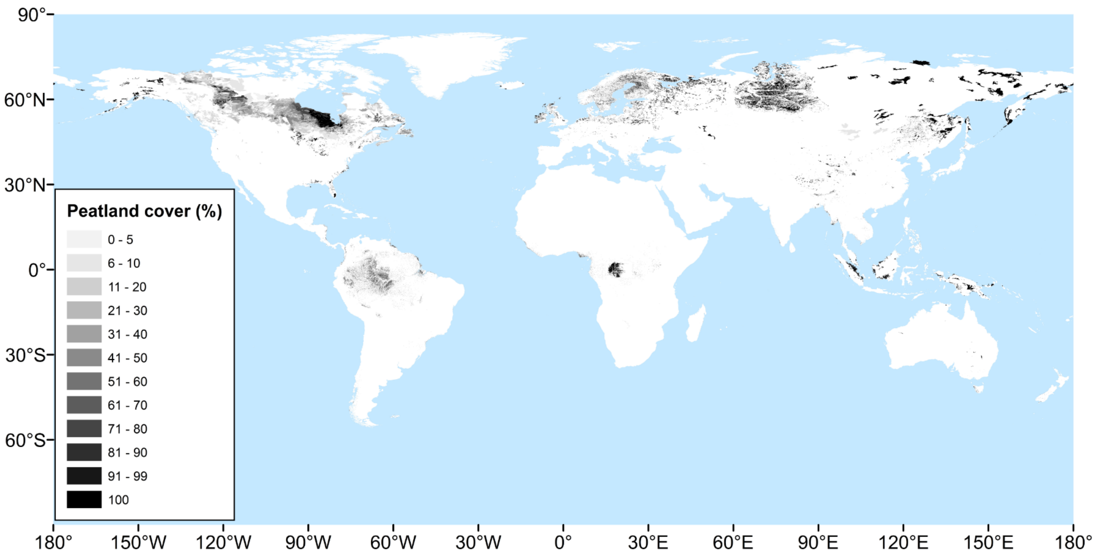

Figure 2.1 Global peatland distribution derived from PEATMAP. The black shading classes indicate percentage peatland cover in Canada, where the source data were provided as grid cells rather than shape files; and regions where peatland cover was estimated from histosols of HWSD v1.2. Elsewhere, where shapefiles are freely available, individual peatlands and peat complexes are shown in solid black.

This study compared estimates of peatland extent derived from PEATMAP to previously published peatland databases and estimates derived from other datasets (Table 2.2): (1) the IMCG-GPD; (2) 'Bog, fen, mire' and 'Swamp forest, flood forest' layers from GLWD-3; (3) the approximation of peatland extent derived from the 'histosols' layer of HWSD v1.2 for the areas where HWSD v1.2 was not used to produce PEATMAP.

Table 2.2 Global breakdown of peatland areal coverage from a variety of estimates, including PEATMAP.

Continent	Country	Land area (km^2) (Worldatlas, 2016)	Peatland area (km^2)			
			IMCG-GPD (Joosten, 2009)	GLWD-3 (Lehner and Döll, 2004)	HWSD v1.2 (FAO, 2012)	PEATMAP (current study)
North America	Canada	9,084,977	1,133,836	201,405	1,074,688	1,132,614
	United States	9,161,923	225,000	5	250,715	197,841
	Others	6,462,100	10,000	6,248	1,967	8,866
	Total	24,709,000	1,368,836	207,658	1,327,370	1,339,321
Asia	Asian Russia	9,784,930	1,176,280	467,162	879,700	1,180,358

Continent	Country	Land area (km^2) (Worldatlas, 2016)	Peatland area (km^2)			
			IMCG-GPD (Joosten, 2009)	GLWD-3 (Lehner and Döll, 2004)	HWSD v1.2 (FAO, 2012)	PEATMAP (current study)
	Indonesia	1,811,569	265,500	24,568	194,008	148,331
	Malaysia	328,657	26,685	20,978	21,480	22,398
	China	9,326,410	33,499	1,381	5,238	136,963
	Others	23,327,434	43,746	12,900	73,680	135,132
	Total	44,579,000	1,545,710	526,989	1,174,106	1,623,182
Europe	European Russia	6,592,812	199,410	5,591	290,908	185,809
	Sweden	410,335	65,623	9	68,469	60,819
	Finland	303,815	79,429	0	92,935	71,911
	United Kingdom	241,930	17,113	9,940	26,902	22,052
	Ireland	68,883	11,090	639	11,142	16,575
	Others	2,562,225	103,751	1,743	143,969	171,171
	Total	10,180,000	504,607	17,923	634,325	528,337
South America	Total	17,840,000	175,603	910,974	102,682	485,832
Africa	Total	30,370,000	130,181	178,814	72,476	187,061
Oceania	Total	7,692,024	72,845	273	6,604	68,636
Global	Total	148,647,000	3,797,782	1,852,631	3,317,563	4,232,369

The estimate of peatland extent derived from PEATMAP exceeds that of IMCG-GPD by a factor of 2.8 in South America, and 1.4 in Africa. These large disagreements are likely due to insufficient information on tropical peatlands in IMCG-GPD, which Joosten (2009) acknowledged. Large areas of peatlands in the swamp forests of South America and Africa have recently been mapped but there may be more to discover (Lawson et al., 2015). For example, a peatland complex covering approximately 145,500 km^2 in the Central Congo Basin, Democratic Republic of the Congo (DRC) was recently reported for the first time by Dargie et al. (2017). These new data, which have included in

PEATMAP, represent an enormous increase in the estimate of peatland extent in the DRC and in Africa more broadly relative to IMCG-GPD (DRC peatland extent was previously given as only approximately 11,900 km^2 in IMCG-GPD). Similarly, the existence of approximately 120,000 km^2 of peat in the Pastaza-Maranon foreland basin, Peruvian Amazonia, has only recently been confirmed by fieldwork (Lähteenoja et al., 2013), and its inclusion in PEATMAP represents a large increase in estimated peat extent compared to IMCG-GPD's estimate of approximately 50,000 km^2 for the whole of Peru.

In Southeast Asia, PEATMAP's estimate of peat extent is lower than that of IMCG-GPD (Table 2.2). This is because many Southeast Asian countries have updated their peatland inventories with new products since IMCG-GPD was published in 2009. The resultant increase in detail and accuracy of national peatland maps in Southeast Asia has led to an overall decrease in peatland area in PEATMAP compared to the IMCG-GPD because many areas previously classified as peatlands in IMCG-GPD have been reclassified as non-peat. For instance, our estimates of peatland extent in Indonesia are 55.87 % of that in IMCG-GPD with the equivalent figure being 83.9 % for Malaysia. In Indonesia, IMCG-GPD estimates of peat extent were derived from previous peatland maps (Wahyunto et al., 2003; Wahyunto et al., 2005; Wahyunto et al., 2006). These peatland maps were produced from the interpretation of satellite images supported by dated land cover maps (RePPProT, 1989) with little ground survey data, especially in Papua (Ritung et al., 2011). The more recently published datasets used in PEATMAP were constructed using a combination of more recent soil surveys, legacy soil data and auxiliary information (e.g. digital elevation models, geological maps, agroclimatic maps). The Indonesian peatland map used in PEATMAP presented by the Indonesian Ministry of Agriculture (Ritung et al., 2011) was adopted as the official government map of peatlands in Indonesia. Similarly, the Malaysian national peatland map used in PEATMAP was published after IMCG-GPD and contains more detailed, up to date source data (Wetlands International, 2010). In addition, peatland area in Chile is estimated at 10,996 km^2 by IMCG-GPD while they cover only 2,276 km^2 according to PEATMAP. IMCG-GDP estimates of peatland extent in Patagonia are approximately equivalent to histosol extent. However, most of these Patagonian histosols have been determined as mangrove and marsh by the data source used in PEATMAP (Gumbricht, 2015), which has a higher spatial resolution and is more up to date than IMCG-GPD.

In the relatively well-studied peat-rich regions in mid- and high-latitudes of the Northern Hemisphere, where IMCG-GPD is better informed than in the tropics, PEATMAP and IMCG-GPD agree more closely. For instance, our estimates of peatland extent in North America are 98.43 % of that in IMCG-GPD, and 104.70 % in Europe. However, there are still some important disagreements between PEATMAP and IMCG-GPD in these areas. For instance, the IMCG-GPD is likely to underestimate peat extent in the United Kingdom and the Republic of Ireland, and to overestimate it in Sweden and Finland. This is because the data used in these regions (Table A.1) were updated by their respective national geological survey agencies after the IMCG-GPD was published in 2009. The more recent data used in PEATMAP have benefitted from new soil surveys (e.g. Republic of Ireland), the latest remote sensing images (e.g. UK Land Cover Map (LCM) 2007 released in 2011) or novel geo-statistical mapping techniques, compared to IMCG-GPD.

Similar patterns can be found when comparing PEATMAP to other existing peatland inventories. Peatland areas in mid- and high-latitude areas of North America, Russia and Scandinavia are estimated at 3,746,200 km^2 by Bord na Móna (1984) and 3,329,239 km^2 by Lappalainen (1996), while they only cover 2,853,955 km^2 according to PEATMAP. In contrast, peatland extent in South America and Africa are estimated at just 135,535 km^2 by Bord na Móna (1984) and 160,000 km^2 by Lappalainen (1996), while they cover 667,834 km^2 according to PEATMAP.

This study queried HWSD v1.2 to extract all pixels where histosols were either a dominant or sub-dominant soil type (Figure B.1). The resulting global area of histosols, approximately 3.3 million km^2 (pixel area multiplied by fraction of histosols), is broadly consistent with the area 3.25-3.75 million km^2 reported by the latest world reference base for soil resources (IUSS Working Group WRB, 2015), but substantially lower than total peatland areas given by PEATMAP and IMCG-GPD.

The global extent of ‘bogs, fens, and mires’ in GLWD-3, approximately 0.8 million km^2, is smaller than the approximately 1.1 million km^2 reported for Canadian peatlands alone (Tarnocai et al., 2011). Including the additional category ‘Swamp forest, Flooded forest’, this estimate rises to approximately 1.9 million km^2, which is still less than half the total global peatland extent estimated by IMCG-GPD, PEATMAP and other oft-cited estimates of approximately 4 million km^2 (e.g. Parish et al., 2008). As such, the GLWD-3 estimate (Figure B.2) seems likely to be a gross underestimation globally, although it probably provides an overestimate in the tropics. Wetland distribution in GLWD-3 is derived from a variety of sources originating from the Global Aeronautical chart, while some wetland classes of GLWD-3 are in the regions where there is only limited ground survey data. Lehner and Döll (2004) also noted that the information for these wetlands could be replaced by that obtained from future ground data efforts. Recent ground data suggests that large proportions of peatlands derived from GLWD-3 are non-peat-forming wetlands (Ritung et al., 2011; Wetlands International, 2010). At higher latitudes, GLWD-3 fails to identify extensive European peatlands that have been drained to reduce flood risk or provide arable land (Joosten, 2009). This is mainly because when wet peatlands are drained they may no longer qualify as wetlands in some databases (Köchy et al., 2015). Similarly, extensive areas of permafrost peatlands have been omitted from GLWD-3's peatland distribution due to their spectral reflectance being similar to other non-peatland permafrost landscapes and being classified as ‘25-50% wetland’, ‘50-100% wetland’ or ‘Intermittent Wetland’ rather than ‘Peatland’.

The number of distinct data sources used to produce PEATMAP was greatest in Europe, followed by Southeast Asia. Figure 2.2 shows the locations of disagreement between PEATMAP and estimates of peatland extent derived from HWSD v1.2 and GLWD-3 in these two regions. Areas of the greatest agreement between PEATMAP and dominant histosols (greater than or equal to 50% of the pixel) in HWSD v1.2 are in extensive, well-documented peatland regions, such as Eastern Europe, central Finland, north Scotland, Indonesia and Malaysia. By contrast, histosol area is much less extensive than areas of swamp forest peatlands in the tropics (e.g. Gumbricht et al., 2017; Junk et al., 2011). Potential for improving the fidelity of PEATMAP's estimates of global peatland distribution seems greatest through new field surveys in those regions where there is large peat coverage but previously limited peatland survey data (e.g. Indonesia). Table 2.2 and Figure 2.2(c) and (d) indicate that GLWD-3 almost certainly underestimates peatland extent in both Europe and Southeast Asia. GLWD-3 failed to classify most of the areas that were determined as peatlands in PEATMAP and HWSD v1.2, meaning that GLWD-3 is often unable to distinguish peatlands from non-peat wetland types in most areas.

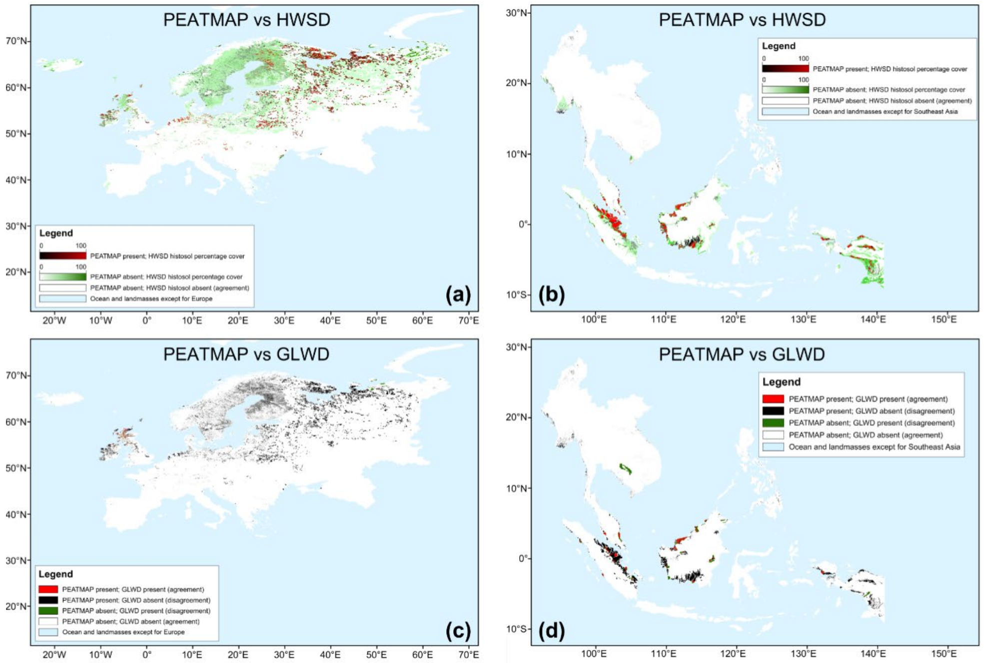

Figure 2.2 Areas of agreement and disagreement between PEATMAP and HWSD v1.2 (panels a and b), and between PEATMAP and GLWD-3 (c and d) for Europe (a and c) and Southeast Asia (b and d). In panels (a) and (b), black to red shading scale indicates percentage cover of histosols according to HWSD v1.2 in those pixels that contain peat according to PEATMAP (i.e. percentage by which PEATMAP overestimates HWSD histosol cover); white to green shading scale indicates percentage cover of histosols according to HWSD v1.2 in those pixels not identified as peat by PEATMAP (i.e. percentage by which HWSD histosol cover overestimates PEATMAP). White indicates pixels not identified as peatlands by either PEATMAP or HWSD v1.2. In panels (c) and (d), red indicates pixels identified as peatlands by both PEATMAP and GLWD-3; black indicates pixels that are only identified as peatlands by PEATMAP and not by GLWD-3; green indicates pixels that are only identified as peatlands by GLWD-3 and not by PEATMAP; white indicates pixels not identified as peatlands by either PEATMAP or GLWD-3.

It should be noted that the various definitions of peatlands employed in the source data of PEATMAP could affect the coherence of PEATMAP. Histosols in HWSD were presented according to the FAO definition of ‘Soils having an H horizon of 40 cm or more of organic soil materials (60 cm or more if the organic material consists mainly of Sphagnum or moss or has a bulk density of less than 0.1) either extending down from the surface or taken cumulatively within the upper 80 cm of the soil; the thickness of the H horizon may be less when it rests on rocks or on fragmental material of which the interstices are filled with organic matter’ (FAO, 1997). However, geological surveys may use 1 m organic layer thickness as the threshold (e.g. British Geological Survey, 2013; Geological Survey of Finland, 2010; Geological Survey of Sweden, 2009). Thus, the areas of peatlands derived from these datasets will be less than the areas of histosols derived from HWSD v1.2. In contrast, Malaysian peatlands in PEATMAP are derived from Wetlands International (2010), who defined peatland as an area with a naturally accumulated peat layer at the surface, with a minimum peat depth of 30 cm. In addition, most tropical peatland maps in PEATMAP are derived from Gumbricht (2015), which is one part of The Global Wetlands Map where peat is defined as ‘at least 30 cm of decomposed or semi decomposed organic material with at least 50 % organic matter’, and peatlands refer to landscapes with peat deposits without specific thresholds for minimum continuous peat area, nor for minimum depths. Therefore, the areas of peatlands derived from these datasets will be larger than the areas of histosols derived from HWSD v1.2.

2.4 Conclusions

Although several existing databases can be used to estimate peatland area at a global scale, most of these are comprised of aspatial data. Existing spatial datasets lack some combination of: i) relevance, ii) fine spatial resolution, and iii) the most recent data in many peat-rich locations. The new global peatland map, PEATMAP, amalgamates the latest national, regional and global, freely-available data sources on peat distribution at fine spatial resolutions, incorporating information derived from digitised soil maps, wetland databases, and satellite imagery. Major challenges in creating a combined map from such diverse data sources included ambiguous or non-uniform definitions of peatlands, mixed spatial resolution, incomplete ground data, and incomplete exploration of some potential forested peatland-rich areas, particularly in the tropics. Some errors in the estimation of peat areas are therefore unavoidable, although we believe PEATMAP represents a substantial improvement over previous estimates of global and regional peatland distributions.

This study estimates total global peatland area to be 4.23 million km^2, approximately 2.84 % of the global total land area. The results refine previous estimates of peatland extent compared to previous global peatland databases. Compared to GLWD-3 and histosols in HWSD v1.2, PEATMAP estimates a larger global area of peatlands; tropical peatland extents appear likely to be overestimated by GLWD-3 and underestimated by HWSD v1.2.

Future estimates of global peatland area seem likely to exceed our estimate as new peatland areas are discovered and incorporated into PEATMAP particularly in the tropics. PEATMAP will be freely available from PeatDataHub (http://peatdatahub.net/) and https://doi.org/10.5518/252 and can be easily updated as and when new data sources come to light. PEATMAP may provide a useful reference for scientists and policy makers interested in global ecosystem biodiversity, climate change, carbon cycles and water resources, and may also help provide support for wetland protection and restoration.

Supporting information

Appendix A Supplementary notes for Chapter 2.

Appendix B Supplementary figures for Chapter 2.

References

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Chapter 3

Global peatland-derived drinking water calculation (Paper II)

Xu, J., Morris, P.J., Liu, J., Holden, J. 2018. Hotspots of peatland-derived potable water use identified by global analysis. *Nature Sustainability*. **1**(5), pp. 246-253.

Abstract:

Peatlands cover approximately 2.84 % of the Earth's land surface and store around 10% of all non-glacial freshwater. However, the contribution of peatlands to global potable water resources is unclear because most peatlands are remote from major population centres, and until now no systematic, global assessment of peatland water resources has been undertaken. Here this study analyses global peatland, population and hydrometric datasets to identify hotspots where peatlands are crucial for water supply, and show that these peat-rich catchments deliver water to 71.4 million people. Water-supply peatlands cover just 0.0015 % of the global land surface, yet provide 3.83 % of all potable water stored in reservoirs. Approximately 85 % of all drinking water delivered directly from peatlands is consumed in the United Kingdom and the Republic of Ireland, meaning that peatlands play crucial roles in the water security of these nations. Globally, only 28 % of water-supply peatlands are pristine or protected, highlighting the urgent need for responsible stewardship. Our findings provide global evidence for the often-assumed role of peatlands in sustainable water resource provision and for informing peatland water-resource protection policies.

3.1 Introduction

Peatlands cover around 4.23 million km^2 (Chapter 2) and represent at least a third of global wetland habitat (Parish et al., 2008). A tenth of the world's non-glacial freshwater is thought to be held in peatlands (Joosten and Clarke, 2002), although this estimate is highly uncertain, and it is unclear how much of this water is readily available as a resource. Nonetheless, water provision is a commonly stated ecosystem service of peatlands. High dissolved organic carbon (DOC) concentrations means that water draining from peatlands usually requires treatment before it can be used for drinking water. Other than DOC, water draining from pristine peatlands is often of good quality, meaning that these landscapes are potentially important to sustainable provision of potable water (Page and Rieley, 1998; Watts et al., 2001; Ritson et al., 2014).

Peatland degradation is thought to be accelerating in temperate (Clark et al., 2010; Fenner and Freeman, 2011), tropical (Moore et al., 2011; Rieley et al., 2008) and boreal (Pastor et al., 2003; Schuur et al., 2008) environments due to rising temperatures and enhanced frequency and severity of droughts. Projected climate change to 2100 is predicted to cause severe degradation of some peatlands (Li et al., 2017), resulting in accelerated peat decomposition, release of aquatic carbon and reduction in peatland water quality (Fenner and Freeman, 2011). In addition, rising temperatures and changing precipitation regimes are likely to increase fire risk in many peatlands (Turetsky et al., 2015; Konecny et al., 2016; Worrall et al., 2006), which further threatens their sustainable provision of water resources. Peatlands are also under threat from exploitation for fuel, timber and drainage for arable land (Joosten, 2009; Price and Ketcheson, 2009; Holden et al., 2015), including palm-oil plantations in Southeast Asia (Tonks et al., 2017). Peatlands close to human populations are at greater risk of exploitation and degradation, but are also likely to play a more important role in water resource provision. There is evidence that artificial drainage, which has impacted approximately 12 % of global peatland area (Joosten, 2009), has led to poorer water quality and enhanced fluvial organic carbon fluxes (Evans et al., 2014; Gibson et al., 2009; Holden et al., 2004). This degradation of water quality will increase costs of water treatment, because the by-products of disinfecting organic-rich waters often contain potential carcinogens which are strictly regulated in many countries (Chow et al., 2003; Haigh, 2006; Moore et al., 2013).

Although peatlands are potentially important water sources for humans, the world’s largest peat complexes (e.g., the Western Siberian Lowlands and the Hudson Bay Lowlands) are remote from major population centres and therefore seem unlikely to play as valuable a role in water resource provision as their large area and high water storage capacity might at first suggest. Little is known about the role of peatlands in providing potable water resources at either global or regional scales. A global synthesis has the potential to identify where human populations are most dependent on peatlands for their water supply services, and where enhanced public and policy attention should therefore be directed towards peatland conservation and stewardship in order to sustain water security in the face of changing climate and land use.

This study developed the Peat Population Index (PPI) to quantify objectively the global coincidence of human population and peatland cover at catchment scales. In PPI hotspots this study investigated in closer detail the contribution of peat-derived water to potable water resources abstracted from both reservoirs and river. The other global index, the Peat Reservoir Index (PRI), which quantifies the catchment-scale contribution of peatlands to potable water abstraction from reservoirs was developed. These indices were used to estimate the quantity of global potable water that has drained from or through peatlands (see Methods in this chapter). This study also investigated the degree of degradation in these water supply peatlands. The findings provide the first global evidence base for establishing the role of peatlands in providing water security, and can be used to inform peatland protection policies in water supply zones.

3.2 Basin scale coincidence of peatland cover and humans

The Peat Population Index (PPI) represents the proportion of peatland cover (Figure C.1) in a catchment multiplied by the catchment's population density (Figure C.2). PPI represents the coincidence of people and peatlands at the catchment scale and identifies locations where a large population may rely heavily on peatlands for ecosystem services such as potable water supply (Figure 3.1). This study used global datasets of peatland cover, population, hydrography, digital elevation, and land-use to calculate proportion of peatland cover and population density in each catchment around the world, from which this study calculated PPI for each catchment.

Use of the Jenks optimisation classification (Jenks, 1967) (see Methods in this chapter) resulted in eight hotspot catchments being identified where PPI is at least 106 persons km^{-2}, indicating populace catchments with high peatland cover. Seven of the eight PPI hotspots are in Western Europe, and the other is in the Florida Everglades, USA.

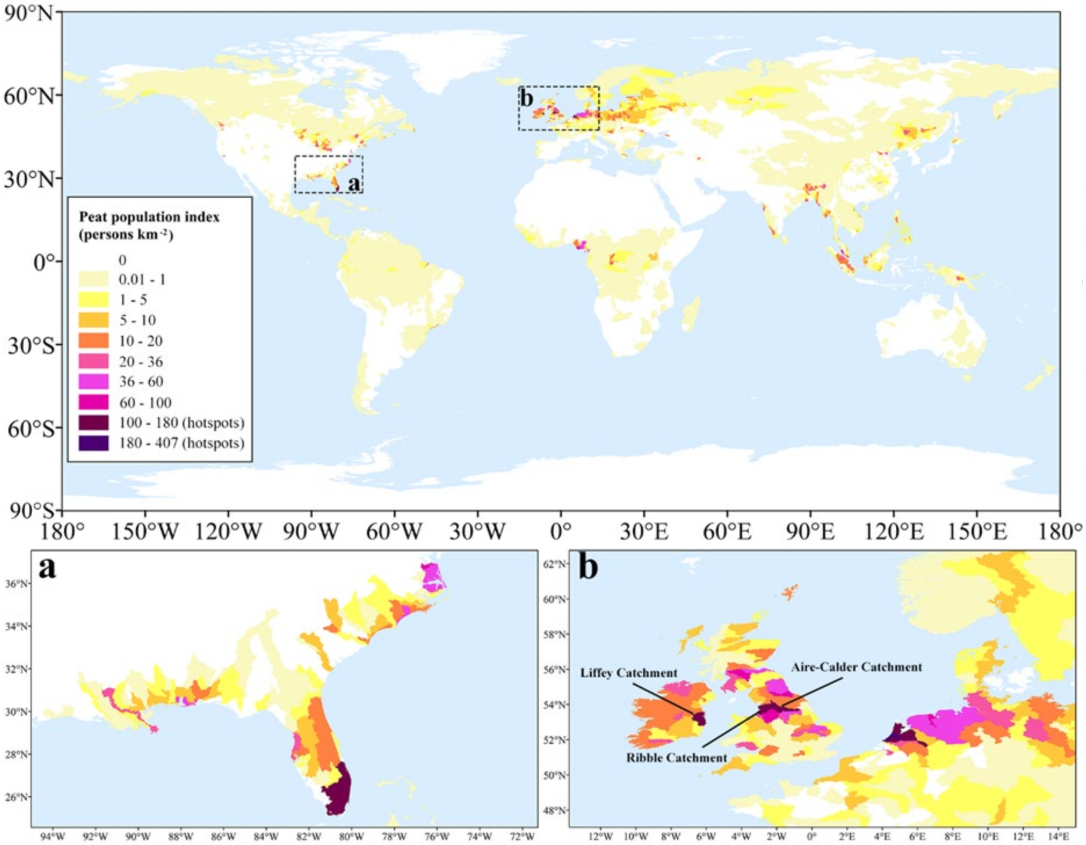

Figure 3.1 Global PPI distribution at the catchment scale, calculated based on the proportion of peatland multiplied by the population density for each catchment. a. PPI hotspot in south-eastern United States, b. PPI hotspots in Western Europe.

The positive correlation between PPI and water supply services in all catchments is challenging to confirm, since often there is confidentiality around water supply systems (e.g. transfer networks, volume of water supplied). Here this study analyses the contribution of peatlands in drinking water supply in PPI hotspots to test the reliability of PPI as an indicator of the importance of peatlands to potable water resource provision (Appendix E). Detailed analysis of river and reservoir water abstraction data reveals that potable water resources in PPI hotspot catchments in the Netherlands and the Everglades are mainly groundwater fed, with relatively little direct supply from peatlands (less than 0.1 %). However, in PPI hotspots in the UK and the Republic of Ireland, peatlands play important roles in providing potable water to large conurbations (Table 3.1). The peatlands responsible for supplying these high volumes of potable water in the UK and Ireland are all situated in upland areas (at least 300 m above sea level). Lowland peatlands in PPI hotspot catchments generally made little contribution to potable water provision, although such peatlands are often drained for agricultural uses, such as in the lowland East Anglian Fens, UK (Bottcher, 1994). Thus, PPI is potentially a useful index to determine where humans make most use of peatlands whether for water supply or other uses. By combining the PPI with digital elevation data, high PPI upland peatland catchments that potentially play important roles in human peatland water use, or high PPI lowland peatland catchments where other uses dominate (e.g. arable, urbanisation, peat extraction) can be determined.

Table 3.1 The characters and potable water provision by peatlands in the eight PPI hotspots catchments.

Catchment	**Area (km^2)**	**Largest City**	**PPI (person km^{-2})**	**Directly-sourced peat-derived water use (million litres day^{-1})**	**Population using directly-sourced peat-derived water (million persons)**	**Country**	**Peatland topographic situation**	**Do peatlands make a contribution to potable water provision?**
Ribble	2,958	Preston	109	78.88	0.52	United Kingdom	Upland	Yes
Aire-Calder	2,514	Leeds	106	25.34	0.17			
Liffey	3,203	Dublin	120	153.99	1.25	Republic of Ireland		
Nieuwe Maas	614	The Hague	180	0.94	0.01	Netherlands	Lowland	Almost none
Oude Rijn	1,083	Utrecht	407					
Nederrijn	2,639	Rotterdam	118					
Zuiderzee	5,136	Amsterdam	137					
Everglades	20,630	Miami	146	<0.01	<0.01	United States		

Since PPI represents the product of peatland cover and population density in a catchment, its value in sparsely-populated but peat-rich catchments is usually low despite extensive peatland cover. For example, the Scandinavian catchment with the largest PPI value is the Glomma catchment in Norway, but the PPI is only 7 persons km^{-2}. Even though this catchment contains 2,840 km^2 of peatland, equivalent to a tenth of the catchment's total area, population density is only 72 persons km^{-2}. Similarly, the largest PPI value in West Siberian catchments is only 5 persons km^{-2} and the PPI values of all catchments in the Hudson Bay Lowlands are less than 1 person km^{-2}.

It should be noted that since the PPI index relates peatland cover in a catchment to population density, the PPI results may be sensitive to the resolution of datasets used (i.e. population, peatland, and catchment boundaries). The modifiable areal unit problem (MAUP) describes the sensitivity of analytical results to the arbitrary choice of the spatial aggregation unit at which data is measured (Openshaw, 1984). The scale at which one chooses to analyse information, be it for the major catchment boundaries, sub-basin catchment boundaries in the AQUASTAT dataset (http://www.fao.org/nr/water/aquastat/maps/index.stm), or even other resolution levels of sub-basin boundaries in HydroBasins (Lehner and Grill, 2013) can produce different PPI values. In addition, classifying the level of PPI based on other grouping schemes (e.g. equal interval, geometrical interval, and standard deviation classification methods) which are different from the Jenks optimisation classification, may result in PPI hotspots that can also be different, even if the units are all of the same scales. Therefore, there is potentially a MAUP in the PPI result although the sub-basin catchment boundaries in the AQUASTAT dataset and Jenks optimisation classification are both widely applied in previous relevant studies (see Methods).

3.3 Global contribution of peatlands to potable water

Peat-fed water supply systems include reservoirs and rivers from which potable water is abstracted, and in which flow accumulation upstream of the abstraction point includes peatland cover. Peatlands are rarely the only sources of water in water supply systems, which are usually also fed by portions of the landscape without peat cover. This study distinguishes between water that has flowed directly through or across peat prior to entering a potable water supply (henceforth, directly-sourced peat-fed water); and the larger volume in a water body that includes a mixture of peat-fed water and water that has not come into contact with peatlands (mixed-source peat-fed water). The total storage capacity of peat-fed water supply reservoirs globally was estimated to be 4.35 km^3, and that they deliver approximately 3.67 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting a population of 63.5 million people on a per capita basis (Table D.1). Regions with the most extensive peat cover (e.g. Western Siberian Lowlands, Hudson

Bay Lowlands; and parts of Scandinavia, Alaska, and Amazonia) are remote from large conurbations and have barely any connection to water supply reservoirs or stream abstraction points. This study identifies 56 peat-fed water supply reservoirs in 34 different catchments; 27 of these catchments are in Europe, three in North America, two in Australia, and one each in Asia and South America. Europe holds 47 of the 56 peat-fed water supply reservoirs (Table D.1).

The Peat Reservoir Index (PRI) is developed to quantify the direct contribution of peatlands to water supply reservoirs on a catchment basis. PRI is defined as the volume of directly-sourced peat-fed water from reservoirs, and complements the use of PPI. For each catchment, the PRI is calculated from the annual volume of domestic water supplied by reservoirs multiplied by the proportion of streams that have interacted with peatlands before draining into those reservoirs (see Methods in this chapter).

The global distribution of PRI is shown in Figure 3.2 and Table D.1. Globally, this study estimates that PRI to be 0.76 km^3 yr^{-1}, meaning that approximately 20.09 % of mixed-source peat-fed potable water from reservoirs is directly sourced from peatlands, equivalent to supporting a population of 13.47 million people on a per capita basis. At the continental scale, abstraction of directly-sourced peat-fed drinking water from reservoirs (PRI) is most important in Europe (689.27 million m^3 yr^{-1}), followed by North America (44.20 million m^3 yr^{-1}), South America (23.50 million m^3 yr^{-1}), Asia (2.04 million m^3 yr^{-1}) and Oceania (0.21 million m^3 yr^{-1}).

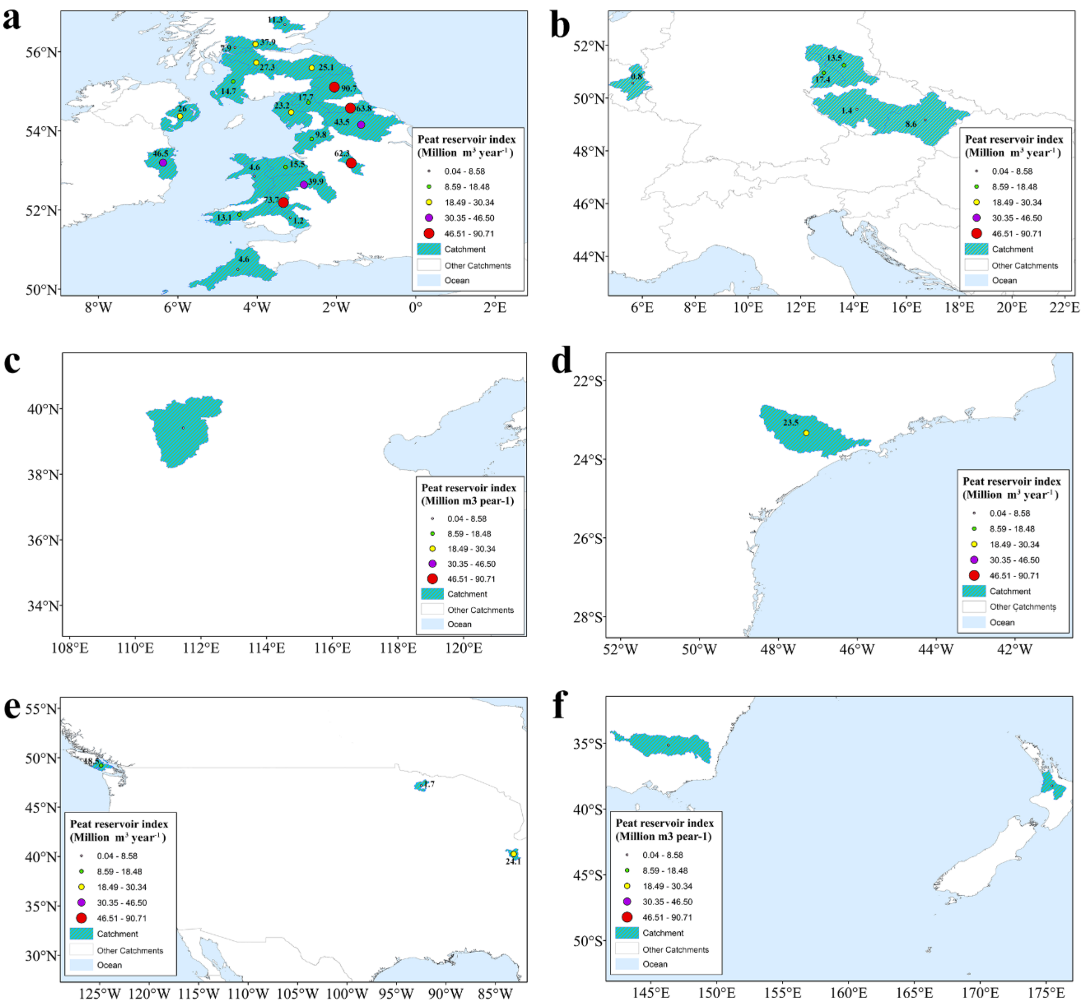

Figure 3.2 Global PRI distribution at the catchment scale. 3.2a the UK and Republic of Ireland, 3.2b Germany, Belgium and the Czech Republic, 3.2c China, 3.2d Brazil, 3.2e United States and Canada, 3.2f Oceania (black numbers represent the PRI values).

Water supply networks commonly transcend topographic catchment boundaries, with drinking water abstracted from reservoirs and distributed to large conurbations in neighbouring catchments. This means that peat-sourced water may still be important in urban catchments where peat cover is low (and which are therefore not identified by PPI) if a sizeable fraction of drinking water is extracted and pumped from neighbouring peat-rich catchments, such as from reservoirs in rural areas. For example, Thirlmere reservoir in the Lake District National Park, England, supplies approximately 226.5 million litres of water per day, while the nearby Haweswater reservoir supplies a further 121.4 million litres of water per day, to settlements in north-west England beyond the boundaries of their own catchments, including Greater Manchester (Table D.1). Therefore, a coincidence of high PPI and high PRI may occur in some catchments (e.g. River Liffey catchment, Republic of Ireland), but not all. Most high PRI catchments are in close proximity to high PPI catchments, even if they are not coincident (Figure 3.3).

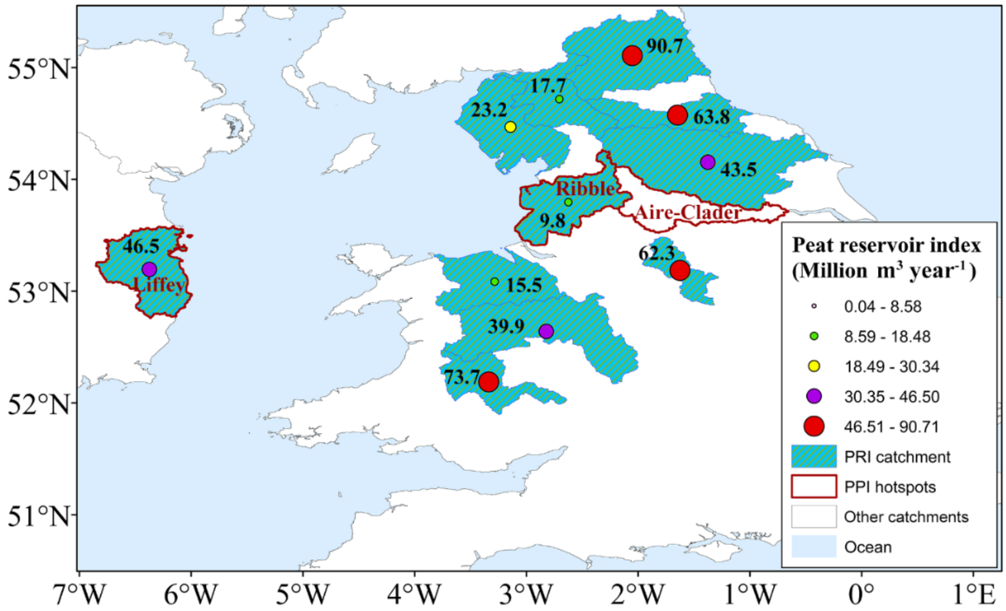

Figure 3.3 Distribution of PPI hotspot catchments and their nearby high PRI catchments in the UK and Republic of Ireland (black numbers represent the values of PRI).

High PPI catchments with peatlands in headwater locations indicate where people are most likely to rely heavily on peatlands to provide potable water resources. The 46 catchments with the highest PPI (the top three PPI categories based on Jenks optimisation classification, with PPI values of at least 36 persons km^{-2}) contain 1,482 km^2 of upland peatland cover. 1,302 km^2 (87.9 %) of these upland water-supply peatlands are concentrated in just five UK and Irish catchments, three of which are identified by our analysis as PPI hotspots and which this study has analysed in closer detail (Appendix E); the remaining two are PRI catchments (Tyne and Tees catchments) that neighbour PPI hotspot catchments. This suggests that mixed- and directly-sourced peat-fed water consumption in PPI hotspots, added to that supplied from neighbouring PRI catchments, provides a representative estimate of the vast majority of global potable water derived from peatlands.

This study estimates the total peatland area that contributes potable water to reservoirs in PRI catchments and to stream abstraction in PPI hotspots (hereinafter referred to collectively as water supply peatlands) to be 2,314 km^2, equivalent to just 0.05 % of global peatland area or 0.0015 % of the global land surface area. However, approximately 3.83 % of potable water stored in reservoirs globally is mixed-source peat-fed water. Water supply peatlands provide approximately 4.22 km^3 yr^{-1} of mixed-source peat-fed potable water globally, which is consumed by 71.4 million people. Approximately 0.80 km^3 yr^{-1} of this is directly-sourced peat-fed potable water, equivalent to supporting a population of 14.27 million people on a per capita basis. The global PRI value of 0.76 km^3 yr^{-1} means that more than 93 % of all directly-sourced peat-fed potable water is reservoir derived. Water-supply peatlands are concentrated in north-western Europe; the vast majority of these are located in catchment headwaters, where they have the potential to exert a strong biogeochemical influence on downstream waters. The UK in particular is heavily reliant on peat-fed reservoirs for potable water provision. UK water-supply reservoirs have a total storage capacity of 1.82 km^3, of which 1.32 km^3 (72.5 %) is peat-fed.

The global analysis of this study identifies that use of potable water delivered by peatlands is highly concentrated in important hotspots. The annual volume of mixed-source peat-fed potable water is particularly high in the UK and the Republic of Ireland, estimated at approximately 1.75 km^3 yr^{-1}. These two nations consume approximately 0.68 km^3 yr^{-1} of directly-sourced peat-fed potable water, equivalent to 85 % of the global consumption of directly-sourced peat-fed water. Peatlands cover 9.12 % of the UK (Chapter 2), although water supply peatlands cover only 0.31 %. Nonetheless, the UK consumes approximately 1.56 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 28.25 million people or 43.1 % of UK population. Out of this potable water volume, 0.63 km^3 yr^{-1} is directly-sourced from peatlands. The Republic of Ireland consumes 0.19 km^3 yr^{-1} of mixed-source peat-fed potable water, equivalent to supporting 4.22 million people or 68 % of the national population. In contrast, the world's largest peatland complexes such as those in Alaska, Western Siberia, the Hudson Bay Lowlands, Scandinavia, and the Amazon and Congo basins are largely unimportant to provision of human drinking water, although they represent huge carbon stores (Page et al., 2011; Yu, 2012)

3.4 Sustainable water supply from modified peatlands

Peatlands are potentially sensitive to land-use change (Holden et al., 2015; Li et al., 2016), and once degradation is initiated these systems can rapidly denude and degrade (Evans and Warburton, 2011). This study used land-use as an indicator of degradation in water supply peatlands around the world by interrogating the Ecosystem-Land Use System (Nachtergaele and Petri, 2011) (see Methods in this chapter). It is estimated that only 651.7 km^2, or 28.17 %, of water supply peatlands globally were unmanaged or protected as of 2010 (Table 3.2), determined from the Global Ecosystem-Land Use System (Nachtergaele and Petri, 2011). Anthropogenic pressures on peatlands may therefore threaten their water supply function (Alexandratos and Bruinsma, 2012). The most common land-use activity on water-supply peatlands is arable and livestock hill farming, particularly in the UK. Overgrazing often leads to peatland erosion and degradation (Dawson et al., 2010; Kechavarzi et al., 2010), while arable cropping on peatlands has resulted in peat mass loss (Couwenberg, 2009; Leifeld et al., 2011) and nutrient loading of water courses (Holden et al., 2017; White and Hammond, 2009). Both activities have been shown to increase fluvial aquatic carbon loss from peatlands which will enhance water treatment costs downstream (Stanley et al., 2012). Upland peatlands in the UK play an important role in potable water provision, and are uniquely and severely degraded in a global context (Evans and Warburton, 2011). In England, up to 96 % of deep peatlands, most of which are located in upland headwaters, are affected by land-management practices and historic pollution (Natural England, 2010). These management activities and historic pollution can be damaging under certain circumstances. Concentrations of DOC in water from UK upland peatlands have increased rapidly in recent decades due to a combination of changes in atmospheric deposition chemistry and peat degradation (Evans et al., 2005). Changes in future climate also further threaten the stability of these peatlands and water treatment costs (Li et al., 2016; Ritson et al., 2014). Removal of peat-laden sediment and DOC from water draining from degraded peatlands represent the largest costs in raw water treatment for water utilities in the UK (Whitfield et al., 2011). For example, in Bamford Catchment, a 200 km^2 upland water supply catchment in Derbyshire, England, Severn Trent Water spend at least \$200,000 per year on removing sediment from raw water to meet drinking water standards (data courtesy of Severn Trent Water). The costs of dealing with further degradation from land management (Haigh, 2006; Moore et al., 2013) or climate change (Li et al., 2017) could be substantial as capital investment in new treatment works are required to cope with water from more degraded peatlands. Such investment can amount to as much as \$1 million and \$3 million per thousand people (South Staffs Water, 2017; Yorkshire Water, 2017), and is compounded by enhanced energy and chemical treatment costs each year. Restoration and protection of potable water supply peatlands in order to improve water quality (Menberu et al., 2017; Worrall et al., 2007) may therefore deliver enhanced sustainability of water supply as well as a reduced cost burden on society (Martin-Ortega et al., 2014).

Table 3.2 Land use on global potable water supply peatlands in 2010.

General land use	Specific land use	Peat area (km^2)	Percentage of peat (%)
Unmanaged or protected	Forest - protected	129.35	5.59
	Grasslands - unmanaged	0.07	0.00
	Grasslands - protected	64.90	2.81
	Shrubs - unmanaged	46.30	2.00
	Shrubs - protected	318.21	13.75
	Agriculture - protected	72.70	3.14
	Sparsely vegetated areas - protected	0.80	0.03
	Open Water - unmanaged	3.23	0.14
	Open Water - protected	16.15	0.70
	Total	**651.70**	**28.17**
Low-intensity agricultural activities	Shrubs - low livestock density	0.02	0.00
Moderate- and high-intensity agricultural activities	Forest - with agricultural activities	34.70	1.50
	Forest - with moderate or higher livestock density	109.34	4.73
	Grasslands - moderate livestock density	23.18	1.00
	Grasslands - high livestock density	152.48	6.59
	Shrubs - moderate livestock density	3.80	0.16
	Shrubs - high livestock density	80.46	3.48
	Rain-fed crops (subsistence/commercial)	4.31	0.19
	Crops and moderate intensive livestock density	675.29	29.19
	Crops and high livestock density	114.24	4.94
	Open water - inland fisheries	12.43	0.54
	Total	**1,210.23**	**52.31**
Settlement	Settlement land	451.65	19.52
Global potable water supply peatlands		**2,313.60**	**100.00**

The PPI has been demonstrated as a potentially useful index which could indicate where humans make most use of peatland ecosystem services - whether for water supply or other uses. Furthermore, PPI, PRI and DEMs can synergistically determine where a lot of people will be most likely to rely on peatlands to provide water resources and estimate the volume of water provision from peatlands.

It should be noted that the estimate of the global volume of potable water supplied by peatlands is a conservative one, since it only considers 87.9 % of upland peatlands in the 46 catchments with the greatest PPI. The global PRI value is also a conservative estimate. The GRanD database used to generate the index includes all reservoirs with a storage capacity of at least 0.1 km^3 and another 3,988 smaller reservoirs (<0.1 km^3) for which data are available (Lehner et al., 2011). However, there are numerous additional small reservoirs with a storage capacity less than 0.1 km^3 which are excluded from the database and therefore from analysis of this study. Reservoirs for which domestic water supply is a secondary use (e.g. those mainly used for producing hydroelectricity) are also excluded (see Methods in this chapter) and therefore represent a further small source of underestimation. Ongoing efforts to develop high resolution, gridded maps of population, topography, surface hydrology, peatland cover and land-use will allow future refinements of estimates of potable water provision from peatlands in this study. However, the estimate of this study is based on the best available data at the time of writing and represents the first global inventory of peatland water resources, which might improve the evidence base on the management of peatlands to achieve the UN’s Sustainable Development Goals for ‘Clean Drinking Water’ and ‘Life on Land’.

3.5 Methods

3.5.1 Peatland spatial data

This study used a recently-published global peatland map (Chapter 2) as the source data for peatland extent. PEATMAP contains spatial data on peatlands that are of direct relevance to peatland extents, possess a fine spatial resolution, and are up to date.

3.5.2 Population database

Global population distribution information was derived from the Gridded Population of the World Version 4 (GPWv4) database (CIESIN, http://dx.doi.org/10.7927/H4D50JX4). GPW V4 is a 30 arc-seconds (c. 1 km at the equator) dataset which contains global population counts, density, urban/rural status, age and gender structures with more than 12,500,000 input units maintained by NASA's Socio Economic Data and Applications Center (SEDAC). For GPW V4, population input data are collected at the highest resolution available from the results of the '2010 round' of censuses, which occurred between 2005 and 2014. Most sources for GPW V4 were national statistical collected data in 2010.

3.5.3 Hydrography dataset

The 15 arc-second digital elevation model (DEM), river network, drainage direction and flow accumulation (FAM) data provided by Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (Lehner, 2013) were used along with the sub-basin catchment boundary datasets provided by AQUASTAT (http://www.fao.org/nr/water/aquastat/maps/index.stm). HydroSHEDS is a gridded global dataset providing information in a consistent format for regional and global scale applications (Lehner, 2013). The flow accumulation (FAM) derived from HydroSHEDS defines the accumulated hydrologic flow values (weight of all cells flowing) into each downslope cell in the output raster, and the outlets of the streams, rivers, or drainage areas have the largest values.

The AQUASTAT dataset delineates major catchment boundaries and sub-basin catchment boundaries based on the HydroSHEDS dataset (e.g. drainage direction, flow accumulation) while the constituent rivers of these catchments (e.g. the Strahler stream order level, river network, catchment names) were derived from the FAO hydrological metadata. To extract more comprehensive information, the 15 arc-seconds (approximately 500 m at the equator) sub-basin boundaries were used rather than major catchment boundaries from AQUASTAT. The sub-basin boundaries of AQUASTAT were based on the HydroSHEDS dataset and delineated based on the Strahler stream order level from FAO hydrological metadata which offers the possibility to split sub-basins at any confluence where the inflowing branches (i.e. a tributary and its main stem) exceed a certain stream order level threshold - level three. Due to catchment boundaries in Siberia being incomplete in AQUASTAT, this study used the HydroBasins level five resolution sub-basin boundary for Siberia (Lehner and Grill, 2013). The level five sub-basin boundary is the closest to that used in AQUASTAT for other regions of the world. It should be noted that this would little affect the calculations of peatland potable water provision for human use, since the population of Siberia is extremely sparse.

3.5.4 Global Reservoir and Dam (GRanD) database

The Global Reservoir and Dam database (GRanD) (Lehner et al., 2011) developed by Global Water System Project contains 6,862 records of reservoirs with a cumulative storage capacity of 6,197 km^3. The GranD includes all reservoirs with a storage capacity of more than 0.1 km^3 and 3,988 smaller reservoirs (<0.1 km^3) for which data are available. The associated reservoir dataset includes attributes that used in this study such as the name of the dam and impounded river, primary or secondary use and the storage capacity of the reservoir.

3.5.5 Calculation of Peat Population Index (PPI)

The Peat Population Index (PPI) was developed to quantitatively describe the coincidence of humans and peatland cover in a catchment. The PPI represents how many people are associated with peatlands in per km^2 of a catchment. This is useful from an ecosystem services perspective as it provides information showing those catchments where a lot of people will be relying heavily on peatlands for a variety of services. For each catchment, PPI was calculated by:

$$PPI_i = DPOP_i \times PPEAT_i = \frac{\sum_{j=1}^{n} APOP_j}{A_i} \times \frac{APEAT_i}{A_i} \tag{1}$$

where PPI_i is the value of Peat Population Index in catchment i (persons km^{-2}). In PPI, the km^{-2} is the unit of catchment area rather than of peatland area, $PPEAT_i$ is the proportion of peatland in a catchment i (range from 0-1), and $DPOP_i$ is the population density of a catchment i (persons km^{-2}).

The processing steps to combine each dataset and estimate the value of PPI in each catchment were as follows:

3.5.5.1 Calculation of peatland area in each catchment

To calculate the area of peatland in each catchment, individual peatlands were identified and ascribed to catchments, by using the ‘Identity’ tool in ArcGIS 10.4 (ESRI ArcGIS Desktop, 2016). The peatland area in each catchment was calculated by:

$$APEAT_i = \sum_{j=1}^{n} APEAT_j \tag{2}$$

where $APEAT_i$ is the area of peatlands in catchment i (km^2), n is the number of peatland polygons in catchment i, i is the code of the catchment. Based on the peatland area and catchment area, the percentage of peatland cover for each catchment was calculated:

$$PPEAT_i = \frac{APEAT_i}{A_i} \tag{3}$$

where $PPEAT_i$ is the percentage of peatlands in catchment i, A_i is the area of catchment i (km^2).

The global peatland abundance as a percentage of each catchment is shown as Figure C.1.

3.5.5.2 Calculating total population in each catchment

The global population density dataset has more than 12.5 million input units which need to be allocated to pixels in each catchment. The 'Zonal Statistics' tool in ArcGIS 10.4 was used to calculate the population density raster within catchments. The population total and density of each catchment were calculated by:

$$APOP_i = \sum_{j=1}^{n} APOP_j \tag{4}$$

where $APOP_i$ is the gross of population in catchment i (km^2), n is the number of population density points in catchment i, i is the code of the catchment and

$$DPOP_i = \frac{\sum_{j=1}^{n} APOP_j}{A_i} \tag{5}$$

where $DPOP_i$ is the population density in catchment i, and A_i is the area of catchment i (km^2).

The population density distribution at the catchment scale is shown as Figure C.2.

3.5.6 Calculation of the Peat Reservoir Index (PRI)

Normally peatlands are not the only water sources for a peat-fed reservoir, as reservoirs could be fed by rivers drained from other non-peatland water sources. Therefore, the proportion of stream flow that interacted with potable water supply peatlands before draining into reservoirs should be considered in order to estimate the volume of potable reservoir water directly supplied by peatlands. Here, the Peat Reservoir Index (PRI) was developed to describe the contribution of peatlands to water supply reservoirs in a catchment, and it indicates the volume of potable reservoir water directly supplied by peatlands (directly-sourced peat-fed potable water). For each catchment, PRI can be calculated by:

$$PRI = \sum_{i=1}^{n} V_{Reservoir(i)} \times P_{Stream(i)} \tag{6}$$

where PRI is the Peat Reservoir Index (million cubic meters per year) in a catchment, $V_{Reservoir(i)}$ is the volume of annual potable water supplied by peat-fed water supply reservoir i (mixed-source peat-fed potable water) (million cubic meters per year), $P_{Stream(i)}$ is the proportion of stream flows that have interacted with peatlands before draining into reservoir *i* (range from 0-1), and *n* is the number of peat-fed water supply reservoirs in a catchment.

The processing steps to combine each dataset and estimate the value of PRI in each catchment were as follows.

3.5.6.1 Identifying potable water supply peatlands

Peatlands not only provide raw water directly for human use but can also alter the quality of the flowing water. Therefore, those peatlands which have interacted with streams before draining into potable water sources (including headwater and riparian peatlands) can be defined as ‘potable water supply peatlands’. The potable water supply peatlands were identified by overlaying PEATMAP (Chapter 2) with the river networks of potable water sources and flow direction data.

3.5.6.2 Identifying peat-fed water supply reservoirs

(1) Identify the potable water supply reservoirs

The GRanD database provides information on the main utility and secondary utility of reservoirs. These reservoirs can be classified into those mainly used for water supply, or those with a different primary purpose (i.e. irrigation, hydroelectricity production, flood control, recreation, navigation, fisheries, pollution control, and livestock water supply) but with a secondary use for water supply. When the water supply was the secondary utility of reservoirs, except in the case of recreation, most of the storage capacity of reservoirs is used for irrigation, hydropower, flood control or navigation rather than providing potable water. Hence the potable water supply function of reservoirs will be overestimated if this study included those. In contrast, many water supply reservoirs are open to the public for recreation, and the utility of recreation does not affect the volume of annual potable water supply. Therefore, in order to avoid overestimation, this study only used reservoirs which are mainly used for water supply, or primarily used for recreation and had a listed secondary use of water supply.

(2) Determine the peat-fed water supply reservoirs

Peat-fed water supply reservoirs refer to those water supply reservoirs for which the impounded streams have interacted with peatlands before draining into the reservoirs. These reservoirs were determined by combining data on water supply reservoirs, PEATMAP and river network systems. As some of the source data of the GRanD database are outdated, some reservoirs in the list may no longer be used for drinking water supply (e.g. Bukowka reservoir in Poland; Vojmsjön in Sweden). In addition, the database cannot distinguish between industrial water supply reservoirs and potable water supply reservoirs (e.g. Spremberg and Pöhl reservoirs in Germany). Therefore, this study checked and then removed 13 reservoirs from the peat-fed potable water supply reservoir list. In addition, there are 1,577 reservoirs in the GRanD database which have no data about their utility. To avoid omitting potential peat-fed water supply reservoirs, the main utility of these reservoirs was determined from the literature, where these reservoirs also occurred in systems with peat present. In total, this added two more reservoirs to the peat-fed potable water supply reservoir list (i.e. Wanjiazhai reservoir in China and Upper Mangatawhiri reservoir in New Zealand). At the same time, to avoid underestimation, this study checked peat-fed reservoirs that are mainly used for irrigation, hydropower, flood control or navigation and had a listed secondary use for water supply to determine if they have recently changed to mainly supply potable water. In total, this added three more reservoirs to the peat-fed potable water supply reservoir list (Poulaphuca reservoir and Vartry Reservoir in the Republic of Ireland and Colby Lake reservoir in the United States). Overall, among the 859 water supply reservoirs in GRanD, there are 56 peat-fed water supply reservoirs. However, the water supply volume of the reservoirs is not provided by GRanD, so here this study extracted data from literature (i.e. statistics, dam plans literature, water company reports, or abstraction licences) to extrapolate the volume of annual water supply from all of these peat-fed water supply reservoirs (part I and part II of Table D.1).

3.5.6.3 Interaction of reservoir input streams and peatlands

(1) Identify the outlets of potable water supply peatlands

Flow accumulation maps display values that represent the number of input cells which contribute water to any other given cell; the outlets of streams or rivers will typically have the largest values. Potable water supply outlets include outlets of rivers draining from (through) peatlands and the river or reservoir abstraction points. If a stream originated from peatlands and flowed through other peatlands within the same catchment, then this study only identified the cell with the largest value of flow accumulation as the peat potable water supply outlet in order to avoid repetitive counting and overestimation.

(2) Proportion of streams with peatlands influence

$P_{Stream(i)}$ refers to the proportion of streams with peat influence before draining into peat-fed water supply reservoirs. $P_{Stream(i)}$ was calculated by the amount of flow accumulation at peatland outlets divided by the value of flow accumulation of the reservoir outlets.

3.5.7 Volume of streams with peatlands influence in PPI hotspots

3.5.7.1 Determining PPI hotspot catchments

In this study, the Jenks optimisation method was used to classify the level of PPI and therefore to determine PPI hotspots. Jenks optimisation allows continuous variables to be binned into meaningful, non-arbitrary categories. Jenks optimisation is a data clustering method designed to determine the best arrangement of values into different classes, seeking to reduce the variance within classes and maximize the difference between classes (Jenks, 1967), and is widely used in geographic information science (Baby et al., 2016; Chen et al., 2013; Sadeghfam et al., 2016). The Jenks optimisation method is also known as the goodness of variance fit (GVF), and the optimization is achieved when the quantity GVF is maximized: (1) Calculate the sum of squared deviations between classes (SDBC); (2) Calculate the sum of squared deviations from the array mean (SDAM); (3) Subtract the SDBC from the SDAM. This output equals the sum of the squared deviations from the class means (SDCM). The method first specifies an arbitrary grouping of numeric data. SDAM is constant and does not change unless data changes. The mean of each class is computed, and the SDCM is calculated. Observations are then moved from one class to another in an effort to reduce the sum of SDCM and therefore increase the GVF statistic. This process continues until the GVF value can no longer be increased.

The threshold of the highest two PPI categories is 106 persons km^{-2} in the catchments by using the Jenks optimisation classification method. There are eight catchments with a PPI value greater than or equal to 106 persons km^{-2} while the PPI values of all other catchments were less than 100 persons km^{-2}. Therefore, in this study, the top eight catchments with a PPI value no less than 106 persons km^{-2} were identified as PPI hotspots. The processing steps to estimate the volume of potable water provided from peatlands in each PPI hotspot catchment were as described below.

3.5.7.2 Determining potable water sources in PPI hotspots

There is no available database that shows the water supply system abstraction points and pathways for redirected potable water within the PPI hotspot catchments. Therefore, for PPI hotspots, this study obtained as much data as possible from currently available data in the public domain (Appendix E).

3.5.7.3 Determining volume of peat-fed stream abstraction

This study: (1) identified the peatlands which have interacted with streams before draining into water sources by combining the distribution of potable water sources, PEATMAP and river network systems; (2) identified the outlets of potable water supply peatlands and peat-fed water sources and calculated the proportion of stream flows which have interacted with peatlands before draining into peat-fed rivers based on the flow accumulation dataset; (3) estimated the volume of annual water directly supplied from potable water supply peatlands in the PPI hotspots (directly-sourced peat-fed potable water) by multiplying the volume of annual water supplied from peat-fed water supply rivers (mixed-source peat-fed potable water) and the proportion of stream flows which have interacted with peatlands before draining into peat-fed water rivers.

3.5.8 Determine upland peatlands in high PPI catchments

There is no standard definition of upland peatlands, but this study applied the term to peatlands more than 300 m above sea level which approximates to definitions commonly used in the UK (Langan and Soulsby, 2001; Soulsby et al., 2002), since most of the potable water supply peatlands are located in the UK.

The threshold of the highest three PPI categories for catchments is no less than 36 persons km^{-2} using the Jenks optimisation classification method. There are 46 catchments with a PPI value of no less than 36 persons km^{-2}. Therefore, in this study, the top 46 catchments with a PPI value no less than 36 persons km^{-2} were chosen as the highest PPI catchments (PPI hotspots are the top eight catchments with a PPI value no less than 106 persons km^{-2}). Upland peatlands in high PPI catchments were isolated using elevation values derived from the 15 arc-second DEM provided by HydroSHEDS by ArcMap 10.4.

3.5.9 Determine land-use status of potable water supply peatlands

The Ecosystem-Land Use System (Nachtergaele and Petri, 2011) is a 5 arc minutes (approximately 9.25 km at the Equator) resolution global land use systems for assessing land degradation, which has been recently developed by FAO in close collaboration with the World Overview of Conservation Approaches and Technologies. This Land Use System contains 36 classes based on a combination of land-cover, agricultural activities (high/medium/low) and management (irrigation/protected/no use). Here this study overlapped global water-supply peatlands with Ecosystem-Land Use System to determine the land use of these peatlands. This study removed from the analysis those land-use types which were not found on water-supply peatlands and then combined some similar land-use categories to aid analysis (Table D.2).

Data availability

The main data supporting the findings of this study are available within the article and its Supplementary Information files. These data and any associated data are available from University of Leeds open access data repository.

Supporting information

Appendix C Supplementary figures for Chapter 3.

Appendix D Supplementary tables for Chapter 3.

Appendix E Supplementary notes for Chapter 3.

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Chapter 4

DOC dynamics in the peat-fed potable water supply catchments in the UK (Paper III)

Xu, J., Morris, P.J., Liu, J., Ledesma, J.L.J., Holden, J. Increased dissolved organic carbon concentrations in peat-fed UK water supplies under future climate and sulphate deposition scenarios. Submitted.

Abstract: Peatlands are globally-important terrestrial carbon stores as well as regional sources of potable water supply. Water draining from peatlands is rich in dissolved organic carbon (DOC), which can be problematic for water treatment. However, it is unclear how future climate and sulfate deposition changes may impact DOC in peatland-derived potable water. The United Kingdom (UK) is a global hotspot that consumes 79 % of all potable water derived directly from peatlands. Here, a physically-based hydrological model and a biogeochemical organic carbon model were used to predict discharge and DOC concentration in nine hotspots of peatland-derived potable water use in the UK under a range of 21st-century climate and sulfate-deposition scenarios. These nine catchments supply 72 % of all peatland-derived water consumed in the UK, and 57 % of the global total, equivalent to the total domestic consumption of over 14 million people. Our simulations indicate that annual discharges will decrease, and that mean annual DOC concentrations will increase under all future scenarios (by as much as 53.4 % annually for the highest emissions scenario). Large increases (by as much as a factor of 1.6) in DOC concentration in the 2090s over the baseline period are projected for autumn and winter, seasons when DOC concentrations are already high in the baseline datasets such that water treatment works often reach their capacity to cope. The total DOC flux is largely insensitive to future climate change because the projected increase in DOC concentration is mostly counterbalanced by the projected decrease in discharge.

4.1 Introduction

Peatlands are organic-rich wetlands formed from poorly decomposed plant detritus. They cover approximately 2.84 % of the global land surface (Chapter 2), yet store between a sixth and a third of all global soil carbon (Gorham, 1991; Limpens et al., 2008; Page et al., 2011; Yu, 2012). DOC flux is the rate of flow of DOC per unit area and is normally measured in units of g C m^{-2} yr^{-1}. This DOC flux is a crucial component of peatland carbon budgets (Dinsmore et al., 2013), and once in the aquatic system DOC is either processed and released to the atmosphere (Clark et al., 2010), or is transported to the ocean where it contributes to acidification of marine waters (Raudina et al., 2017). The removal of DOC is a major cost associated with potable water treatment (Martin-Ortega, et al., 2014; Ritson et al., 2014, 2016; Whitehead, et al., 2006). Although DOC does not pose a health risk itself, chlorination of DOC can yield carcinogenic by-products such as trihalomethanes (Chow et al., 2003). The concentrations of these by-products are strictly regulated in most countries and so removal of DOC is required, usually via intensive treatment that requires high amounts of energy and chemical dosage. Increases in DOC concentration in surface water bodies in peatland catchments have been widely reported in the northern hemisphere over the past decades which may due to climate change or atmospheric acid deposition decline (Erlandsson et al., 2008; Freeman et al., 2004). If such increases in DOC concentration continue, considerable expenditure in new water treatment plants and operational cost increases are likely to be required in areas that are reliant on peatland-derived water.

In order for DOC to enter water bodies, organic matter must be first solubilised by physicochemical and biological decomposition processes, and then mobilised through subsurface and overland flow. The biological processes and hydrological processes together control the production of DOC, while hydrological processes primarily govern export (Evans et al., 2006). Temperature and water availability are key drivers of peat accumulation and decomposition and are also important for DOC production rates. Increased atmospheric deposition of sulphate will suppress organic matter solubility and then lower DOC concentrations (Monteith et al., 2007), while reduced sulphate deposition can cause significant increases in solubility and aquatic DOC concentrations (Evans et al., 2006).

Projections of 21st-century climate change for the UK forecast warmer, more humid winters and springs; and warmer, drier summers and autumns (Jenkins, 2009). Current estimates indicate decreased sulphate deposition during the same timeframes (IPCC, 2014; Lamarque et al., 2013). All of these projected changes would appear to indicate increased DOC concentrations in the future, but until now there has been no attempt to quantify the degree of any future increases in DOC for peatland-derived drinking water on a large scale. This study used the Integrated Catchments model for Carbon (INCA-C) (Futter et al., 2007) and the derivative rainfall-runoff model Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport (PERSiST)

(Futter et al., 2014) to simulate future changes in discharge, DOC concentration and DOC flux for nine catchments in the UK that are most reliant on peatland-derived drinking water under 21st-century climate and sulphate deposition scenarios. The UK's unique role as the world's dominant consumer of peatland-derived water (Chapter 3) means that this nine study catchments represent hotspots of peatland water use at not only the national scale but also globally. These nine catchments supply 72 % of all peat-derived water consumed in the UK, and 57 % of the global total, equivalent to the total domestic consumption of over 14 million people (Chapter 3).

4.2 Materials and methods

4.2.1 Study sites

There are nine major peat-fed drinking water supply catchments in the UK (Figure 4.1). The peatland extent was derived from PEATMAP (Chapter 2). The characteristics of these catchments together with climate, hydrological, and chemical parameters observed between 2005 and 2016 are shown in Table F.1.

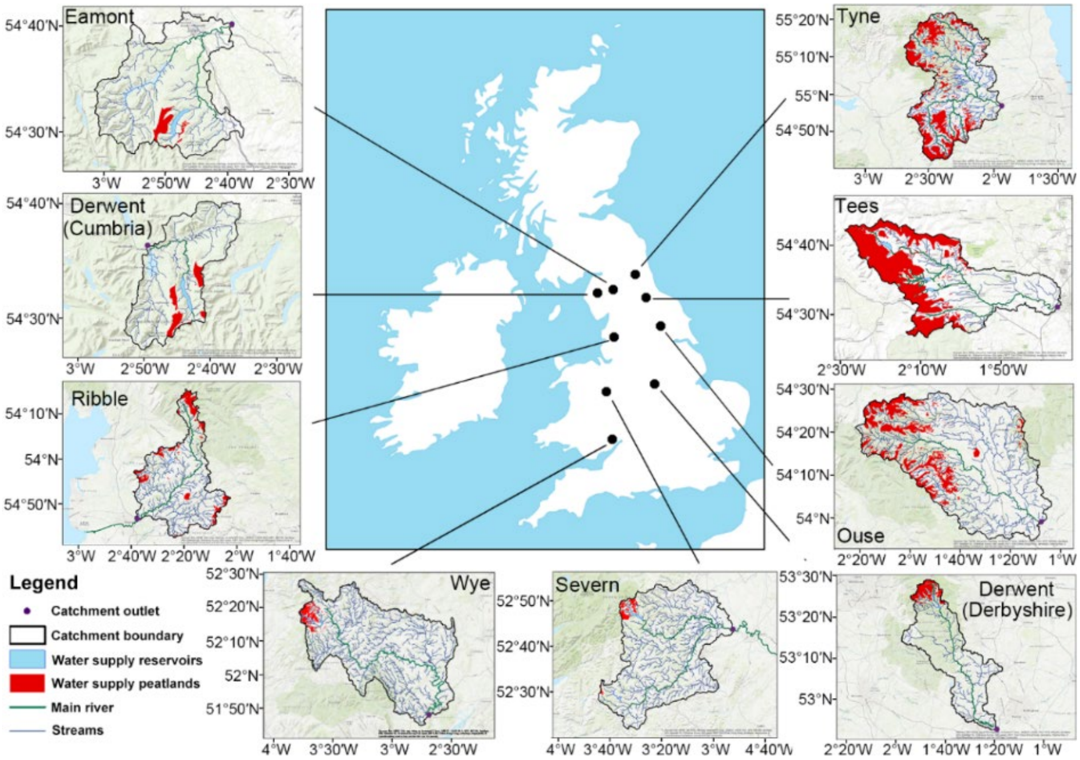

Figure 4.1 Distribution of nine key peatland water supply catchments in the UK.

4.2.2 Peatland DOC model selection

Various peatland DOC models have been established over the past few decades. These may be useful to predict what might happen under future climate and atmospheric deposition scenarios to DOC concentrations and fluxes in peat-fed water supply catchments where potable water must be treated to remove the DOC. To determine a suitable model for the above this study considered: (1) model availability; (2) the model's ability to capture DOC driver factors including rainfall, temperature, and acid deposition; (3) input data availability. Table 4.1 shows a summary of widely-used DOC models which have been employed in peatlands. Only MADOC (Rowe et al., 2014) and Integrated Catchments Model for Carbon (INCA-C) (Futter et al., 2007; Futter and de Wit, 2008) are physically-based models which consider the variables of temperature, rainfall and atmospheric deposition (i.e. sulphate). However, MADOC is more suitable for use over small scales (approximately 100 km^2) than for large catchments. Since this project is focussed on large scale research, using MADOC in this project would require huge amounts of detailed input data, most of which are currently unavailable. Therefore, INCA-C was deemed the most suitable available model to examine the impact of future climate change and atmospheric deposition on DOC release in peatland water supply catchments. The following section provides a brief introduction to the INCA-C model.

The required input data for INCA-C includes daily time series of precipitation, soil moisture deficit (SMD; the difference between the current depth of water and the water holding capacity), hydrologically effective rainfall (HER; the fraction of precipitation which contributes to runoff), temperature (in °C), and precipitation (in mm) for the available dates within the simulation period. HER is the depth of precipitation or snowmelt, net of evaporation that can enter the upper soil horizon while SMD is an estimate of the difference between the amount of water in the soil and the amount of water it can hold. HER and SMD can be derived from a separate hydrological model - Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport (PERSiST) (Futter et al., 2014). As input data, PERSiST requires daily time series of air temperature and precipitation.

As well as time-series data some values used in the parameterisation of the INCA-C model are fixed and site-specific. For example, size of the catchment (ha), length and width of stream reach (m), latitude of the site (important for estimating insolation) and proportion of land-cover type (e.g. bog, moorland, forest, grassland, arable, urban) in the catchment.

Table 4.1 A summary of widely-used DOC models which have successfully been employed in peatland studies.

Model types	Example	Note	Rainfall	Temperature	Acid deposition
Statistical models	Creed et al. (2008)	Relating DOC concentrations in stream water to watershed hydrology, catchment characterises, or climate	Yes	No	No
	Monteith et al. (2015)		No	Yes	Yes
	Grayson et al. (2012)		Yes	Yes	No
Soil moisture and temperature models	Birkenes model (Grieve, 1991) Modified Birkenes model (Boyer et al., 2000)	Physically-based. Net DOC production and loss is essentially regulated by soil temperature, and transport is regulated by soil moisture content, snowmelt, run-off and soil percolation	Yes	Yes	No
Hydrology-biogeochemistry models	Soil carbon submodule of CENTURY Model (Parton et al., 1988)	Physically-based. The model requiring input information on climate (temperature and precipitation), soil properties (soil texture, soil pH, bulk density, field capacity, wilting point, initial organic and mineral soil C, N, P, and S), and plant chemistry characteristics (e.g. lignin content, nutrient content)	Yes	Yes	No
	Dynamic DOC model (Michalzik et al., 2003)	Physically-based. Combines soil carbon production and loss functions for multiple soil layers and includes a simple hydrological model to simulate soil moisture and runoff processes	Yes	Yes	No
	MADOC (Rowe et al., 2014)	Physically-based. Integrating existing models of vegetation growth and soil organic matter turnover, acid-base dynamics, and organic matter mobility	Yes	Yes	Yes
	INCA-C (Futter and de Wit, 2008; Futter et al., 2007)	Physically-based. Simulating soil carbon stocks and DOC in an arbitrary number of user-specified land cover types	Yes	Yes	Yes

Model types	Example	Note	Rainfall	Temperature	Acid deposition
	ECOSSE (Smith et al., 2010a; Smith et al., 2010b)	Physically-based. Comprehensively relating stream DOC driven by daily weather and litterfall, variations in catchment cover types and soil conditions (upper and lower layers on uplands and wetlands) and hydrological flow paths	Yes	Yes	No
	Durham Carbon Model (Worrall and Burt, 2005)	Semi-physically based. Formulating DOC production and storage processes in the upper soil layers of a peat bog as affected by soil temperature and water-table fluctuations with monthly resolution in the context of climate change and land management	Yes	Yes	No

An advantage of INCA-C is that this model can simulate effects of hydrological, climate- and atmospheric deposition-related variables on not only daily stream DOC concentration and fluxes, but also different types of overland flow dynamics (which may be important for DOC concentrations and fluxes) in an arbitrary number of user-specified land-cover types at large catchment scale and regional scales.

4.2.3 PERSiST and INCA-C modelling

INCA-C describes the major factors and processes controlling DOC in surface waters that have been reported in the literature, which is used in this paper to simulate DOC concentration and flux under present and future climate and sulphate conditions. There are four components to INCA-C: (1) a GIS interface used to define the geographic information of catchment, such as catchment boundary and the areas of different land-cover classes, (2) an external rainfall-runoff model used to calculate hydrologically effective rainfall (HER) and soil moisture deficits (SMD), (3) a land phase hydrochemical model simulating material fluxes through the soil column and transformations between chemical stocks, and (4) an in-stream model simulating the transformations in the aquatic phase (Futter et al., 2007). The model operates on a daily time step. It represents the major stores of organic carbon in the terrestrial and surface water environments, and the in-soil and instream processes that determine the transfer of carbon between these stores. Carbon stores and transformations represented in the model are shown in Figure 4.2.

INCA-C requires an input time series of both observed and calculated parameters. The required HER and SMD are estimated based on the observed daily air temperature and precipitation by using an external rainfall-runoff model. Measured surface water DOC concentrations and streamflow data are needed for model calibration. The terrestrial hydrological sub-model in INCA-C simulates three water stores corresponding to water pooled on the soil surface and shallow groundwater in upper and lower soil horizons (Figure 4.2). Water in the upper soil box may return to the soil surface as saturation-excess runoff, percolate to the lower soil compartment, or be lost to the reach as diffuse runoff. Saturation- and infiltration-excess overland flows are modelled separately as water in the former will have interacted with the soil and hence will have different carbon concentrations than water in infiltration-excess overland flow. All water entering the lower soil box eventually reaches the stream. The biogeochemical carbon sub-model simulates the theoretical transformations between different carbon pools. Carbon pools include DOC, soil organic carbon (SOC), potentially dissolved carbon (PDC) and dissolved inorganic carbon (DIC). Organic carbon is transformed from the solid to dissolved phase and vice versa. DIC is produced from mineralization of DOC and SOC. Both DOC and DIC are transported from the soil to the stream through diffuse flow. More details about INCA-C model including the model differential equations have been described by Futter et al. (2007).

Precipitation, Evapotranspiration and Runoff Simulator for Solute Transport (PERSiST) is a semi-distributed model which not only can simulate the daily stream flow, but also can generate the required input data (HER and SMD) for INCA-C. The required input data for running PERSiST are daily air temperature and precipitation, catchment areas, the proportional coverage of different land-cover types in the catchment, and reach (river or stream) information including length and average width. The required input data for calibration is measured streamflow. More details about PERSiST have been described by Futter et al. (2014).

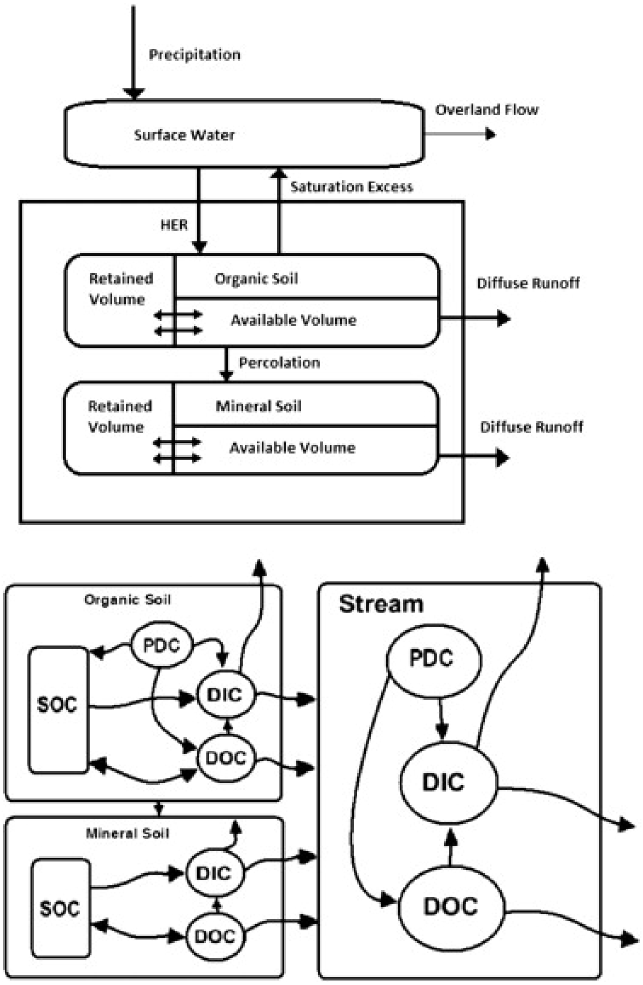

Figure 4.2 Conceptualization of the two interconnected sub-models within INCA-C. The upper diagram shows the hydrological sub-model with theoretical fluxes between water pools. The lower diagram depicts the biogeochemical carbon sub-model with theoretical transformations between different carbon pools. Carbon pools include DOC, soil organic carbon (SOC), potentially dissolved carbon (PDC) and dissolved inorganic carbon (DIC). Hydrologically effective rainfall (HER) is the fraction of precipitation which contributes to runoff (Futter et al., 2007).

4.2.3.1 Required input data for this study

The daily data of precipitation and temperature for the study catchments were derived from ‘UKCP09 (5km resolution) daily climate data sets (1960s-2016)’ (http://data.ceda.ac.uk/badc/ukcp09/data/gridded-land-obs/gridded-land-obs-daily/); the basic information, daily river discharge of outlets (1970s-2016) and land-cover of the catchments was derived from the ‘UK National River Flow Archive dataset’ (http://nrfa.ceh.ac.uk); Sulphate deposition data - both marine and non-marine loads (1990s-2016) - were derived from ‘United Kingdom Eutrophying & Acidifying Pollutants: Precip-Net’ (https://uk-air.defra.gov.uk/networks/network-info?view=precipnet). Gaps in the data of

UKEAP (<0.1 %) have been filled by linear interpolation between known values.

4.2.3.2 Model calibration data for this study

The daily river discharge at outlets (1970s-2016) of the catchments was derived from the ‘UK National River Flow Archive dataset’ (http://nrfa.ceh.ac.uk). DOC concentration at the catchment outlet was derived from the ‘Water Quality Archive’ developed by the Environment Agency (http://environment.data.gov.uk/water-quality/view/download). The archive provides DOC concentration at the outlets for 2005-2016 for all sites except that there was a shorter data duration available for the Tyne (2006-2015), Tees (2006-2016) and the Wye (2005-2013) catchments. Sampling frequencies varied between the nine catchments, ranging from sub-weekly to monthly.

4.2.3.3 Model calibration, evaluation and sensitivity analyses

The baseline period of available datasets was divided into two parts: the first part (2005-2010) was used for calibration and the second part (2011-2016) was used for evaluation. During calibration, slightly shorter periods were available for the Tyne (2006-2010), Tees (2006-2010) and Wye catchments (2005-2009). During evaluation, slightly shorter periods were available for the Tyne (2011-2015) and Wye (2010-2013) catchments. The calibration strategy for PERSiST and INCA-C followed the steps described by Futter et al. (2014) and Ledesma et al. (2012).

PERSiST was calibrated and then used to generate time series of soil moisture deficit (SMD; the difference between the current depth of water and the waterholding capacity) and hydrologically effective rainfall (HER; the fraction of precipitation which contributes to runoff) for running INCA-C. At first, a preliminary manual calibration was performed to maximize the R^2 and N-S (Nash and Sutcliffe, 1970) statistics comparing observed to modelled stream flows. This parameter set was then used as the basis for a Monte Carlo exploration of the parameter space. During each iteration of the Monte Carlo analysis, 100 loops of 600 runs were used for the identification of each parameter set candidate. In all cases, parameters values were sampled from a rectangular prior distribution. The initial boundaries of the rectangle were defined as ±25 % of the parameter value for the best performing initial manual calibration. After each iteration of the Monte Carlo analysis, parameter sensitivity was assessed using the 100 best performing parameter sets, which were defined by ranking the R^2 and N-S statistics comparing modelled and observed DOC. The cumulative parameter distributions derived from the best performing parameter sets were compared to rectangular distributions, and if non-rectangular, the parameter range was adjusted prior to the next iteration of the Monte Carlo analysis. This process was terminated when the Monte Carlo analysis failed to provide any improvement in R^2 and N-S values over the preceding set of model runs. Finally, a single best-performing parameter set from the 100 loops was selected for final best parameter, which was then used to generate time series of SMD and HER. Parameters of PERSiST model used in MC analysis are listed in Table 4.2.

Table 4.2 Parameters of PERSiST model used in MC analysis.

Parameter	Units	Description
Snow threshold	°C	Temperature threshold for liquid or solid water
Snow multiplier	/	Adjustment factor relating measured precipitation to estimated snowfall
Rain multiplier	/	Adjustment factor relating measured precipitation to estimated rainfall
Degree day melt factor	mm $°C^{-1}$	Temperature-dependent rate at which snow melts
Degree day ET	mm $°C^{-1}$	Maximum possible temperature-dependent rate at which evapotranspiration occurs
Growing degree threshold	°C	Temperature threshold above which evapotranspiration can occur
Snow interception	mm	Depth of precipitation intercepted by canopy when air temperature is less than or equal to the snow threshold
Rain interception	mm	Depth of precipitation intercepted by canopy when air temperature is greater than the snow threshold
Snow multiplier	/	Adjustment factor relating measured precipitation to estimated snowfall
Rain multiplier	/	Adjustment factor relating measured precipitation to estimated rainfall
a	/	Flow velocity multiplier
b	/	Flow velocity exponent
Infiltration offset	mm	Offset for different water level baselines between reach and buckets receiving infiltration
Max capacity	mm	Maximum depth of water that can be held in the bucket

Parameter	Units	Description
Retained water depth	mm	Depth below which water no longer freely drains
Runoff time constant	d	Characteristic time constant for water drainage
Relative ET	/	The fraction of total evapotranspiration in a landscape unit occurring in a given bucket
ET adjustment	/	Exponent for limiting evapotranspiration
Infiltration	mm	The maximum depth of water that may infiltrate into a bucket from any source
Drought runoff fraction	/	The fraction of incoming precipitation contributing to runoff when the soil water will not freely drain
Relative area index	/	Fraction of surface area covered by bucket
Inundation threshold	mm	The depth at which water from the reach can inundate a hydrologic response unit type
Porosity	/	The void fraction of a bucket (used for calculating height of the water column)

The calibration strategy for INCA-C followed a slight adaptation to the approach described for PERSiST and by Ledesma et al. (2012). It should be noted that the initial manual calibration was not only need to be done in hydrological sub-model but also in the biogeochemical sub-model. The parameters controlling the hydrological sub-model were fixed once the performance from manual calibration was similar to the best parameter set performance for PERSiST. Parameters for the biogeochemical sub-model were first calibrated manually, after which ranges for the Monte Carlo analysis were defined as ±25 % of the parameter value for the best performing manual calibration. The Monte Carlo tool was then run to find the best-performing dataset (from 100 loops of 300 runs). Parameter sensitivity was assessed using the 100 best performing parameter sets in an analogous manner as in PERSiST. Finally, the best-performing parameter sets for PERSiST and INCA-C were examined through being employed for modelling the flow and DOC in the catchment with the evaluation periods. Parameters of INCA-C model used in MC analysis are listed in Table 4.3.

Table 4.3 Parameters of INCA-C model used in MC analysis.

Parameter	Units	Description
Base Flow Index	/	fraction of water that goes to the lower layer from the upper layer
Threshold soil zone flow	$m^3\ s^{-1}$	the threshold flow from the soil at which there is return flow to the direct runoff layer
Rainfall excess proportion	/	fraction of the hydrologically effective rainfall (HER; precipitation net of evapotranspiration) that goes to the direct runoff layer
Maximum infiltration rate	mm day^{-1}	the maximum amount of water that can be infiltrated from the direct runoff layer to the upper layer in a day
Flow a	/	flow velocity multiplier (dimensionless)
Flow b	/	flow velocity exponent (dimensionless)
DOC -> DIC self-shading factor	mg L^{-1}	as DOC increase, factor decreasing the rate in which DOC is mineralized to DIC as a consequence of photodegradation
DOC -> DIC radiation multiplier	kg $m^2\ kW^{-1}$	multiplier controlling the rate of photodegradation (DOC to DIC) in the aquatic system
Open water DOC -> DIC microbial	day^{-1}	velocity in which DOC is transformed into DIC in the stream as a consequence of microbial degradation
Organic layer SOC to DOC	day^{-1}	the rate at which SOC is transformed into DOC in the upper layer
Organic layer SOC to DIC	day^{-1}	the rate at which SOC is transformed into DIC in the upper layer
Mineral layer SOC to DOC	day^{-1}	the rate at which SOC is transformed into DOC in the lower layer
Mineral layer SOC to DIC	day^{-1}	the rate at which SOC is transformed into DIC in the lower layer
Organic layer PDC to SOC	day^{-1}	the rate at which PDC is transformed into SOC in the upper layer
Organic layer PDC to DIC	day^{-1}	the rate at which PDC is transformed into DIC in the upper layer
Organic layer PDC to DOC	day^{-1}	the rate at which PDC is transformed into DOC in the upper layer

Parameter	Units	Description
Direct runoff PDC to DOC	day^{-1}	the rate at which PDC is transformed into DOC in the direct runoff layer
Organic layer DOC to SOC	day^{-1}	the rate at which DOC is transformed into SOC in the upper layer
Organic layer DOC to DIC	day^{-1}	the rate at which DOC is transformed into DIC in the upper layer
Mineral layer DOC to SOC	day^{-1}	the rate at which DOC is transformed into SOC in the lower layer
Mineral layer DOC to DIC	day^{-1}	the rate at which DOC is transformed into DIC in the lower layer
Organic layer b1	/	parameter *b1* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soil solution, i.e. limiting the SOC desorption into DOC, such as *dDOC/dt = -(k2 + b1 · [anion]exp b2) · DOC + k1 · SOC*
Organic layer b2	/	parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soil solution, i.e. limiting the SOC desorption into DOC, such as *dDOC/dt = -(k2 + b1 · [anion]exp b2) · DOC + k1 · SOC*
Mineral layer b1	/	parameter *b1* to determine the decrease in carbon solubility in the mineral layer when there is a strong acidifying anion (i.e. sulphate) present in the soil solution, i.e. limiting the SOC desorption into DOC, such as *dDOC/dt = -(k2 + b1 · [anion]exp b2) · DOC + k1 · SOC*
Mineral layer b2	/	Parameter *b2* to determine the decrease in carbon solubility in the mineral layer when there is a strong acidifying anion (i.e. sulphate) present in the soil solution, i.e. limiting the SOC desorption into DOC, such as *dDOC/dt = -(k2 + b1 · [anion]exp b2) · DOC + k1 · SOC*
Organic layer retention volume	m^3	amount of water per km^2 in the upper layer below which water no longer freely drains
Mineral layer retention volume	m^3	amount of water per km^2 in the lower layer below which water no longer freely drains

Parameter	Units	Description
Direct runoff residence time	days	characteristic time constant for water drainage
Organic layer residence time	days	characteristic time constant for water drainage
Mineral layer residence time	days	characteristic time constant for water drainage
Zero rate depth	/	parameter used to regulate transformation rates at different moisture conditions. Above a specified SMD ('Zero rate depth'), processes are turned off
Max rate depth	/	parameter used to regulate transformation rates at different moisture conditions. Above a specified SMD ('Zero rate depth'), processes are turned off, below they linearly increase until the base level at another specified SMD value ('Max rate depth')
Max rate fraction at box max capacity	/	parameter used to regulate transformation rates at different moisture conditions. Below the 'Max rate depth', another parameter ('Max rate fraction at box max capacity') controls the decrease in transformation rates until $SMD=0$
Thermal conductivity of soil	W m^{-1} K	thermal conductivity of the soil
COUP_10Degree Response	/	it multiplies the process rates by the specified value for every 10 degrees increment with respect to the base level soil temperature at which the processes are multiplied by 1
COUP_BaseT	/	the base line soil temperature at which the process rates are 1 (°C)
Litterfall	kg ha^{-1} day^{-1}	the amount of literfall per unit of area per day in the catchment
Fast pool fraction	/	fraction of the total SOC in the upper layer that belongs to the fast pool

Sensitivity analysis of discharge and DOC-related parameters was assessed by varying best performing parameter sets by ± 25 % in an analogous MC method (de Wit et al., 2016). For each parameter, the Kolmogorov-Smirnov (KS) test was used to compare the ensemble of values from the 100 parameter sets to a rectangular distribution. A significant KS statistic ($p<0.05$) implied that the posterior distribution was not rectangular and thus that stream flow or DOC simulations were sensitive to the specific parameter (Futter et al. 2014).

4.2.4 Future climate and sulphate deposition scenarios

Future time was separated into two periods: 2030-2039 (termed here 2030s) and 2090-2099 (termed here 2090s).

Future daily climate projections over the 21st-century were derived from the United Kingdom Climate Projection 2009 (UKCP09) (Jenkins, 2009) which were produced based on Met Office Hadley Centre's climate model (Pope et al., 2000) and Intergovernmental Panel on Climate Change (IPCC) Special Report of Emission Scenarios (Nakicenovic et al., 2000). There are three scenarios in UKCP09: high emission (A1F1), medium emission (A1B) and low emission (B1). At the time of writing, the UKCP09 data are the most up-to-date, publically-available, downscaled climate projections for the UK.

Temperature and precipitation changes with respect to baseline conditions (Figure G.1 and G.2) were calculated based on UKCP09 outputs. There were 100 possibilities for each variable. In order to capture the likely change of each variable, values of central estimates (50 % probability level) were taken in this study.

Future sulphate deposition dynamics were derived from the estimations from the Atmospheric Chemistry and Climate Model Intercomparison Project (Lamarque et al., 2013). In Europe, the sulphate deposition for the 2030s will decrease to 36 % of the baseline level, and for 2090s will decrease to 18 % of the baseline level.

Six future scenarios were considered: (1) 2030s B1: combinations of future precipitation and temperature under the lowest emission (or UKCP09 B1) with projected sulphate deposition in the 2030s; (2) 2030s A1B: combinations of future precipitation and temperature under medium emission (or UKCP09 A1B) with projected sulphate deposition in the 2030s; (3) 2030s A1F1: combinations of future precipitation and temperature under the highest emission (or UKCP09 A1F1) with projected sulphate deposition in the 2030s; (4) 2090s B1: combinations of future precipitation and temperature under the lowest emission (or UKCP09 B1) with projected sulphate deposition in the 2090s; (5) 2090s A1B: combinations of future precipitation and temperature under medium emission (or UKCP09 A1B) with projected sulphate deposition in the 2090s; and (6) 2090s A1F1: combinations of future precipitation and temperature under the highest emission (or UKCP09 A1F1) with projected sulphate deposition in the 2090s.

4.3 Results and discussion

4.3.1 Model performance for baseline simulation period

4.3.1.1 Model calibration and evaluation

PERSiST simulated values fitted observations of discharge well (Table 4.4). Normally, applications of hydrological models resulting in model performances of at least N-S>0.5 for flow simulations are considered good (Moriasi et al. 2007). Modelled discharge captured the seasonal variations, and the timing of the rising and falling limbs (Figures 4.3 and 4.4) with R^2 ranging from 0.47 to 0.79 and N-S values ranging from 0.46 to 0.73 in the calibration periods, and with R^2 ranging from 0.44 to 0.78 and N-S values ranging from 0.42 to 0.75 in the evaluation periods.

Table 4.4 Descriptive statistics (range, mean, and standard deviation) for the baseline periods for all the nine catchments.

		Discharge (m^3 s^{-1})			DOC concentration (mg L^{-1})		
Catchment		**Mean**	**Standard Deviation**	**Median**	**Mean**	**Standard Deviation**	**Median**
Tyne	Simulated	46.53	46.08	32.88	9.49	2.96	8.92
	Observed	48.46	57.35	29.70	9.79	3.71	9.02
Wye	Simulated	82.91	89.87	50.76	3.17	0.98	3.05
	Observed	73.34	79.89	44.80	3.21	1.52	2.81
Tees	Simulated	21.99	32.12	11.49	7.77	3.07	7.26
	Observed	21.52	29.00	12.40	8.45	3.93	7.18
Derwent (Derbyshire)	Simulated	25.11	17.33	19.97	3.30	0.82	3.25
	Observed	18.75	19.10	12.80	3.32	0.92	3.06
Ouse	Simulated	59.01	52.66	40.38	5.94	2.25	5.59
	Observed	57.35	65.00	33.43	6.28	3.19	5.41
Severn	Simulated	49.52	42.72	34.92	4.22	1.02	4.12
	Observed	45.76	53.30	23.88	4.46	1.78	4.02
Ribble	Simulated	44.74	50.73	27.11	5.71	2.39	5.23
	Observed	36.14	50.32	17.10	6.01	2.30	5.29
Derwent (Cumbria)	Simulated	16.39	16.81	10.59	1.69	0.51	3.57
	Observed	13.75	14.21	9.25	1.75	0.61	4.44
Eamont	Simulated	22.59	22.74	14.01	2.17	0.63	2.00
	Observed	18.53	24.07	10.20	2.33	0.80	2.17

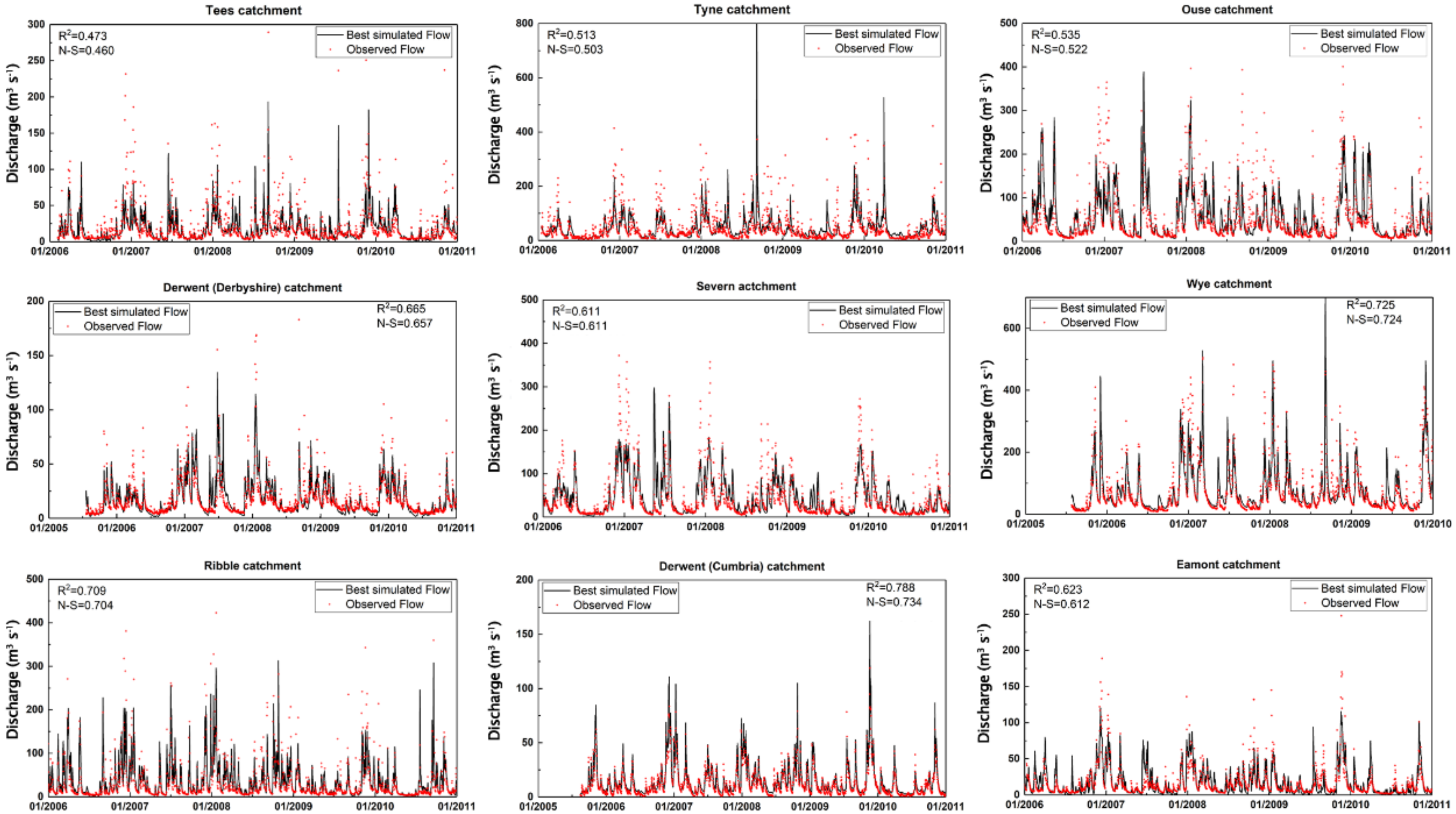

Figure 4.3 Comparison of observed and simulated discharge for the Tyne, Tees, Wye, Derwent (Derbyshire), Ouse, Severn, Ribble, Derwent (Cumbria) and Eamont catchments for the calibration periods.

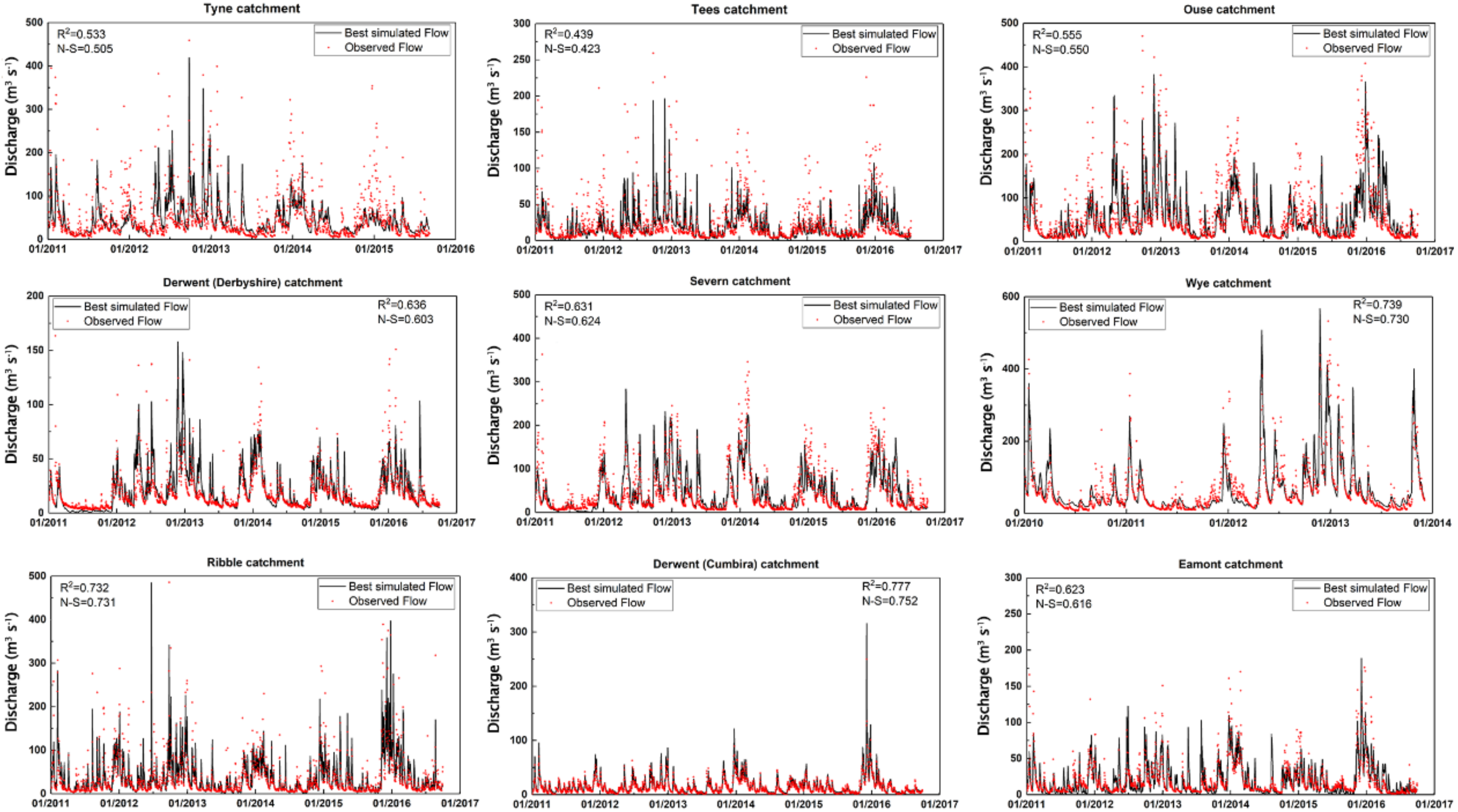

Figure 4.4 Comparison of observed and simulated discharge for the Tyne, Tees, Wye, Derwent (Derbyshire), Ouse, Severn, Ribble, Derwent (Cumbria) and Eamont catchments for the evaluation periods.

Overall, both dynamics and absolute values of DOC concentrations were well captured by the INCA-C model simulations, resulting in R^2 ranging from 0.38 to 0.62 and N-S values ranging from 0.37 to 0.59 in the calibration periods, and R^2 ranging from 0.29 to 0.69 and N-S values ranging from 0.20 to 0.65 in the evaluation periods (Figure 4.5 and 4.6). For the baseline periods, mean simulated daily DOC concentration ranged, respectively, from 1.69 mg L^{-1} (Derwent (Cumbria) catchment) to 9.49 mg L^{-1} (Tyne catchment), similar to the calibration period (Table 4.2). INCA-C successfully reproduced intra-annual (seasonal) dynamics of DOC at the study sites, indicating that it is able to handle variations in soil moisture, temperature control and sulphate deposition. As INCA-C is a multi-parameterized process-based model it simulates complex catchment-wide interdependent processes in soil and stream systems across large catchments. The values of R^2 and N-S are therefore considered acceptable (Futter et al. 2009, Futter et al. 2011, Oni et al. 2012). In addition, the 20 best performing INCA-C parameter sets were retained for estimation of uncertainty bands for daily concentration. Only 6.6 % of total DOC concentration observations outside the 95 % confidence interval of the DOC simulations based on the 20 best parameter sets. Thus, the calibrated models have the potential to be used for long-term and future scenario analysis. However, it should be noted that the model provided a better fit during periods when DOC concentrations were low. The under-predicted high DOC concentrations observed during the late summer and early autumn. This is mainly because the calibration strategy used here involves attempts to minimize the sum of squares between modelled and observed values. As each observation is weighted equally and there are many more observations at low DOC concentrations, the calibration is biased toward fitting the more frequent observations of low DOC concentration. In the future, methods for reducing this bias in the calibration strategy for improving the INCA-C model should be considered. Methods could include different weighting of the observed data, improved algorithm or workflow for calibration and uncertainty analysis on biased observations (e.g. Jajarmizadeh et al., 2017; Oliver et al., 2018; Onyutha, 2019).

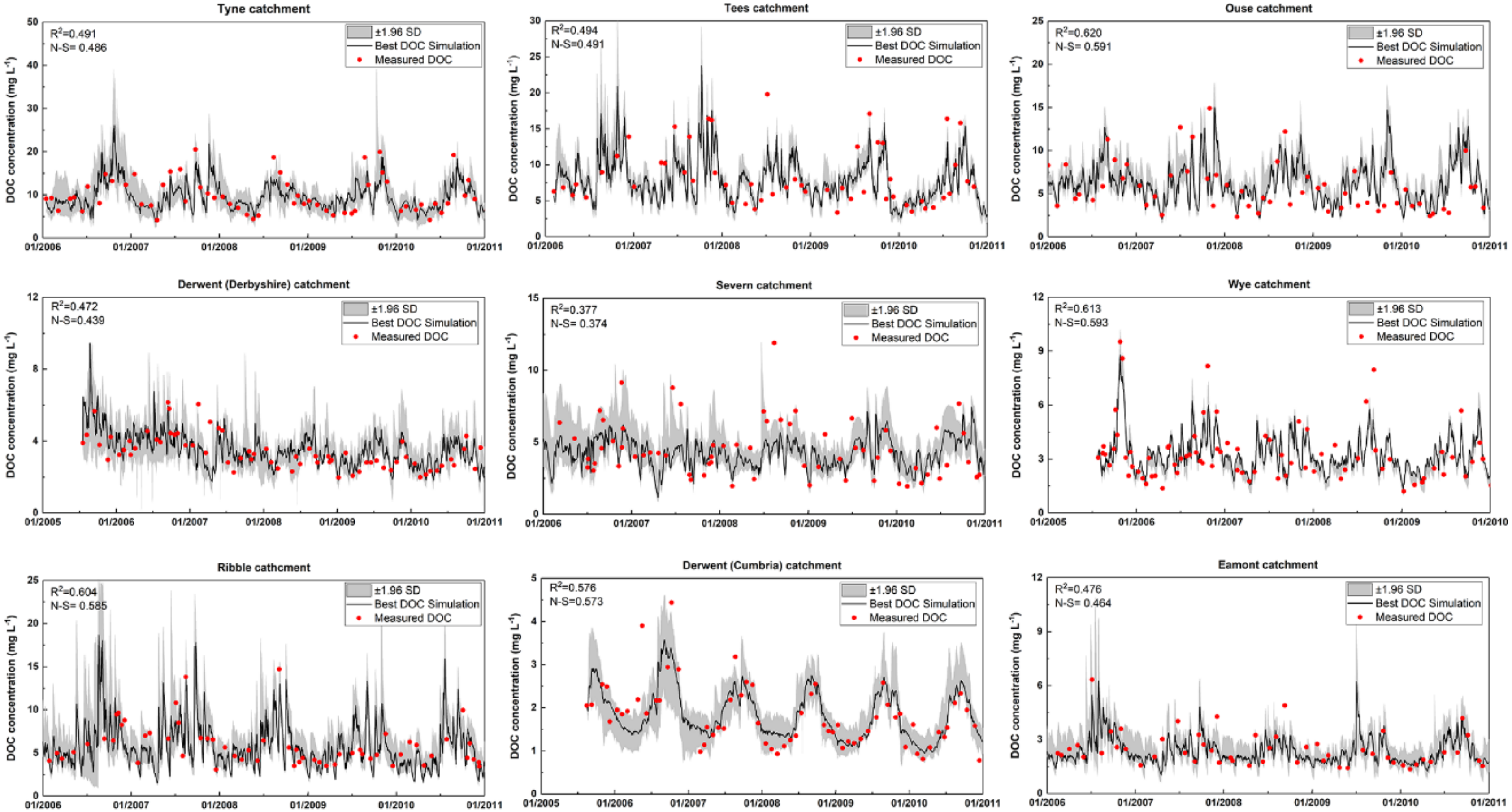

Figure 4.5 Comparison of observed and simulated stream water DOC concentrations at the Tyne, Tees, Wye, Derwent (Derbyshire), Ouse, Severn, Ribble, Derwent (Cumbria) and Eamont catchments for the calibration periods. The line shows simulated DOC concentrations from the best-performing parameter set. The shaded area shows the 95 % confidence interval of the DOC simulations based on the 20 best-performing parameter sets.

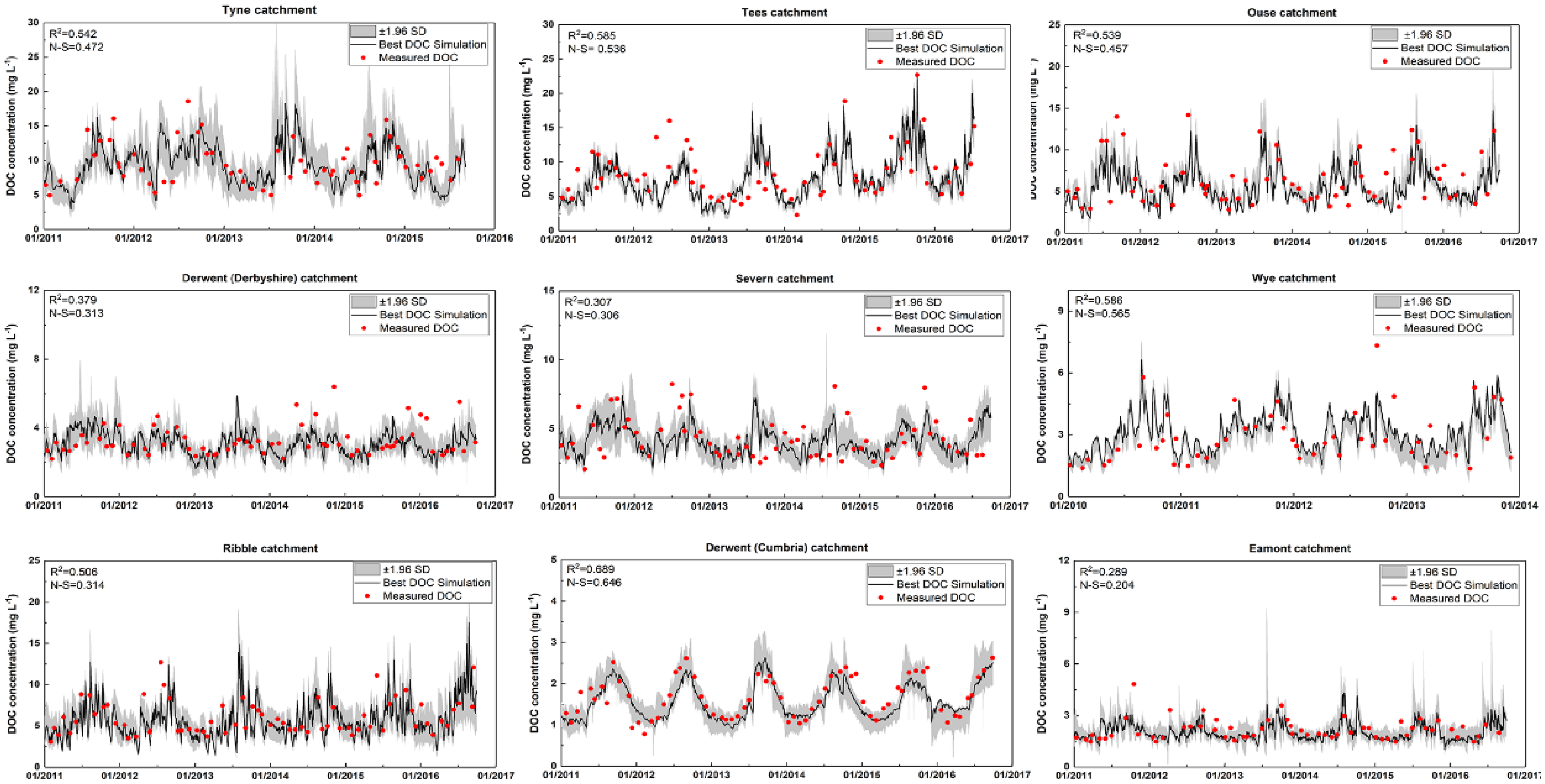

Figure 4.6 Comparison of observed and simulated stream water DOC concentrations at the Tyne, Tees, Wye, Derwent (Derbyshire), Ouse, Severn, Ribble, Derwent (Cumbria) and Eamont catchments for the evaluation periods. The line shows simulated DOC concentrations from the best-performing parameter set. The shaded area shows the 95 % confidence interval of the DOC simulations based on the 20 best-performing parameter sets.

4.3.1.2 Sensitivity analysis

The list of statistically sensitive PERSiST hydrological and INCA-C model parameters for simulation of discharge and DOC concentrations in the calibration period, identified with the Monte Carlo analysis, is presented in Table F.2 and F.3. At least two of the four precipitation-related parameters (flow velocity modifier *b*, adjustment factors *RainMultiplier*, *SnowMultiplier*, and *ResidenceTime*) were the most sensitive to perturbations in discharge modelling (Table F.2). The parameter *b* is used to define flow velocity (as $V = a \times Q^b$, where V is equal to streamflow velocity, and Q is stream discharge) which impacts the stream flashiness. The *RainMultiplier* and *SnowMultiplier* are the adjustment factors relating measured precipitation to estimated rainfall and snowfall, respectively. *ResidenceTime* represents the residence time of water in a soil box as a proxy for the hydraulic conductivity of that particular soil box. In addition, the temperature-related parameters *GrowingDegreeThreshold* and *DegreeDayEvapotranspiration* were among the sensitive parameters for discharge modelling. The *GrowingDegreeThreshold* is the temperature threshold above which evapotranspiration can occur (°C), and *DegreeDayEvapotranspiration* is the depth of water lost due to evapotranspiration per degree per day when the temperature exceeds the limit at which evapotranspiration occurs. Therefore, discharge modelling is highly affected by the precipitation and temperature for the baseline period, which is consistent with findings in previous studies (Jin et al. 2012, McIntyre et al. 2005, Oni et al. 2012).

Sensitivity analyses of DOC modelling (Table F.3) indicate that simulated DOC concentration was highly dependent on soil hydrological (*flow_b* and *base flow index*), thermal (*COUP_10DegreeResponse*), and chemical properties (*OrganicLayerB2* and *MineralLayerB2*). The definition of the *flow_b* parameter is the same as the *b* parameter in PERSiST. The *base flow index* parameter represents the fraction of water that is transferred from upper to lower model storage, which can affect the response time of subsurface water, and therefore controlling streamflow from precipitation and snowmelt. The *COUP_10DegreeResponse* parameter is the thermal conductivity of the soil and a parameter controlling process-rate responses to a 10°C change in soil temperature. It represents the increase in biological production with soil temperature, which is a very sensitive temperature-related parameter. The *OrganicLayerB2* and *MineralLayerB2* are the parameters that determine the DOC desorption rate in the upper (organic) and lower (mineral) soil layers to changes in chemistry and were also sensitive in most cases. This is not surprising since the biological processes that control the production of DOC are all governed in turn by temperature and pH, while DOC export is controlled by hydrological processes. A combination of higher temperatures, reduced precipitation and reduced sulphate deposition in the future thus seems likely to lead to considerably higher DOC concentrations at peak times of the year.

4.3.2 Annual discharge and DOC projections

Simulations for all future scenarios agree on reduced annual discharge in the 2030s and 2090s compared to the baseline period (Figure 4.7). Projected changes in mean annual discharge ranged from -27.4 % to -2.9 % in the 2030s, with a mean of -12.1 % across all nine catchments; and -40.1% to -2.8 % in the 2090s, with a mean of -15.6 % across the nine catchments. All scenarios indicated projected increases in average monthly DOC concentrations in all nine catchments between the baseline period 2006-2016 and the 2030s, and that these increases would continue into the 2090s (Figure 4.8, Table F.4 and Table F.5).

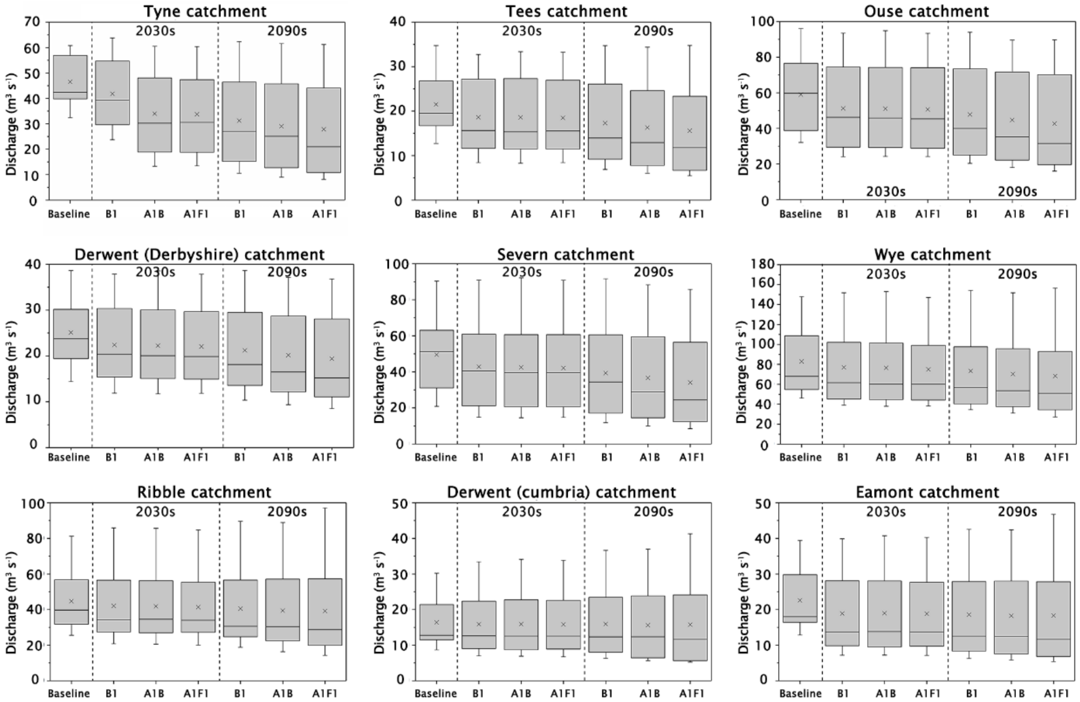

Figure 4.7 Distributions of mean annual average discharge for each site, during the baseline observational period and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) scenarios for the decades 2030s and 2090s. Box heights represent upper and lower quartiles of DOC concentration; centerlines represent medians; crosses represent means; whiskers show the maximum and minimum values.

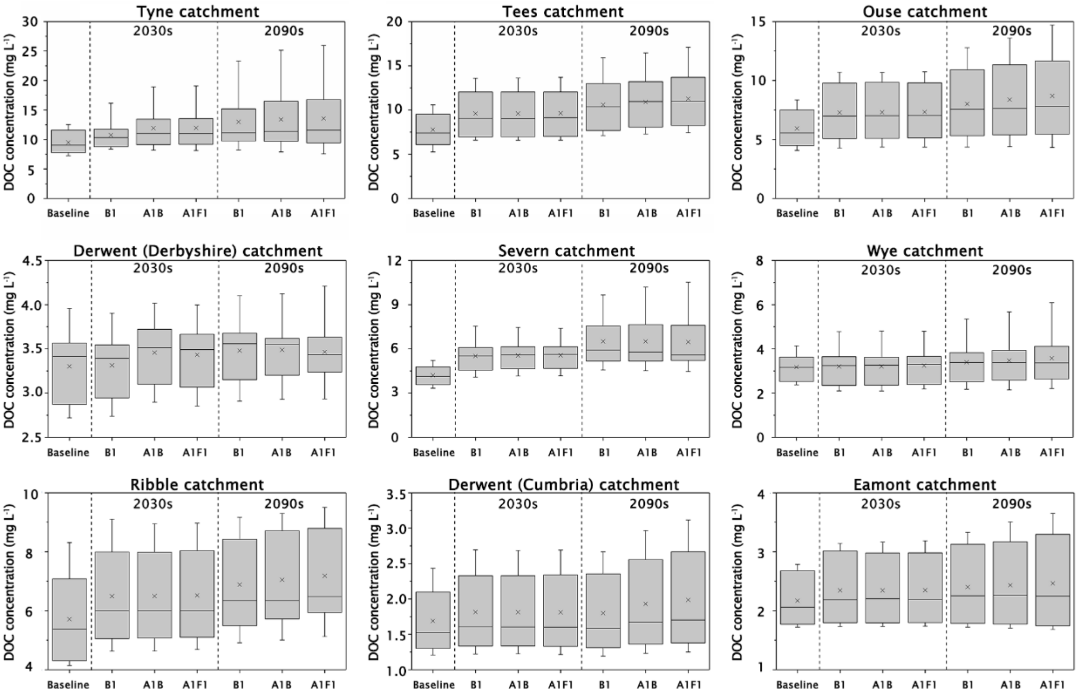

Figure 4.8 Distributions of mean annual average DOC concentrations for each site, during the baseline observational period and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) scenarios for the decades 2030s and 2090s. Box heights represent upper and lower quartiles of DOC concentration; centerlines represent medians; crosses represent means; whiskers show the maximum and minimum values.

Mean annual average DOC concentrations are highest in the Tyne catchment, and lowest in the Derwent (Cumbria) catchment during both the observational baseline period (2006-2016) and under all future scenarios. The Tyne catchment delivers 91 million m^3 of directly-sourced peat-fed potable water per year during the baseline period, more than any other drinking water supply catchment in the world. The Wye and Tees catchments deliver 74 million m^3 and 64 million m^3 of directly-sourced peat-fed potable water per year respectively during the baseline period (Chapter 3).

Between the baseline period and the 2030s, annual average DOC concentration is projected to increase by between 0.3 % under the lowest greenhouse gas (GHG) emissions scenario (in the Derwent (Derbyshire) catchment) and by as much as 31.9 % under the highest emissions scenario (Severn catchment), with a mean increase of 14.8 % across all catchments and future scenarios. By the 2090s, projected average annual DOC concentrations based on mean daily data will have increased compared to the baseline period by between 5.4 % (Derwent (Derbyshire) catchment, lowest emissions scenario) and 53.4 % (Severn catchment, highest emissions scenario), with a mean average increase of 26.5 % across all catchments and future scenarios. Except for the Derwent (Derbyshire) and Severn catchments, where the greatest DOC concentrations are projected under the intermediate emission scenario (A1B), average DOC concentrations are projected to rise monotonically in the direction of increasing emissions. However, in the 2090s, the differences between the average DOC concentrations under the A1F1 scenario and the A1B scenario for Derwent (Derbyshire) and Severn catchments are quite small, and within the margin of statistical error. The difference is 0.71% for Derwent (Derbyshire) and 0.94% for Severn catchment, while for the other catchments studied, the equivalent mean increase of DOC concentration is 3.19% under A1F1 scenario compared to those under A1B scenario (Table F.4).

By the 2090s, the mean DOC concentrations under the A1F1 scenario are projected to be larger than those under the A1B scenario in the Derwent (Derbyshire) and Severn catchments from January to July. However, these increases would be counterbalanced between August and November, since the mean DOC concentrations under the A1F1 scenario are projected to be smaller than those under the A1B scenario in this period (Figure 4.9). The behaviour of the Derwent (Derbyshire) and Severn catchments could be because of differences in precipitation (negatively correlated to DOC concentration). The increase above the baseline of monthly precipitation is larger in the latter part of the year (November), compared to mid-summer (July) under A1F1 by 11.85% for the Derwent (Derbyshire) and by 11.83% for the Severn catchment. For the other catchments studied the equivalent mean difference is 10.84% (Figure G.2). Therefore, DOC in the Derwent (Derbyshire) and Severn catchments may be more diluted under A1F1 than that under the A1B scenario between August and November. The mean annual precipitation and standard deviations of daily precipitation for the Derwent (Derbyshire) catchment are the lowest of all the catchments studied (Table F1). These factors may contribute to a narrow range of DOC concentration change under the different climate scenarios for the Derwent (Derbyshire) except for the period when future precipitation is projected to have the largest increase (December to February, Figure G.2)

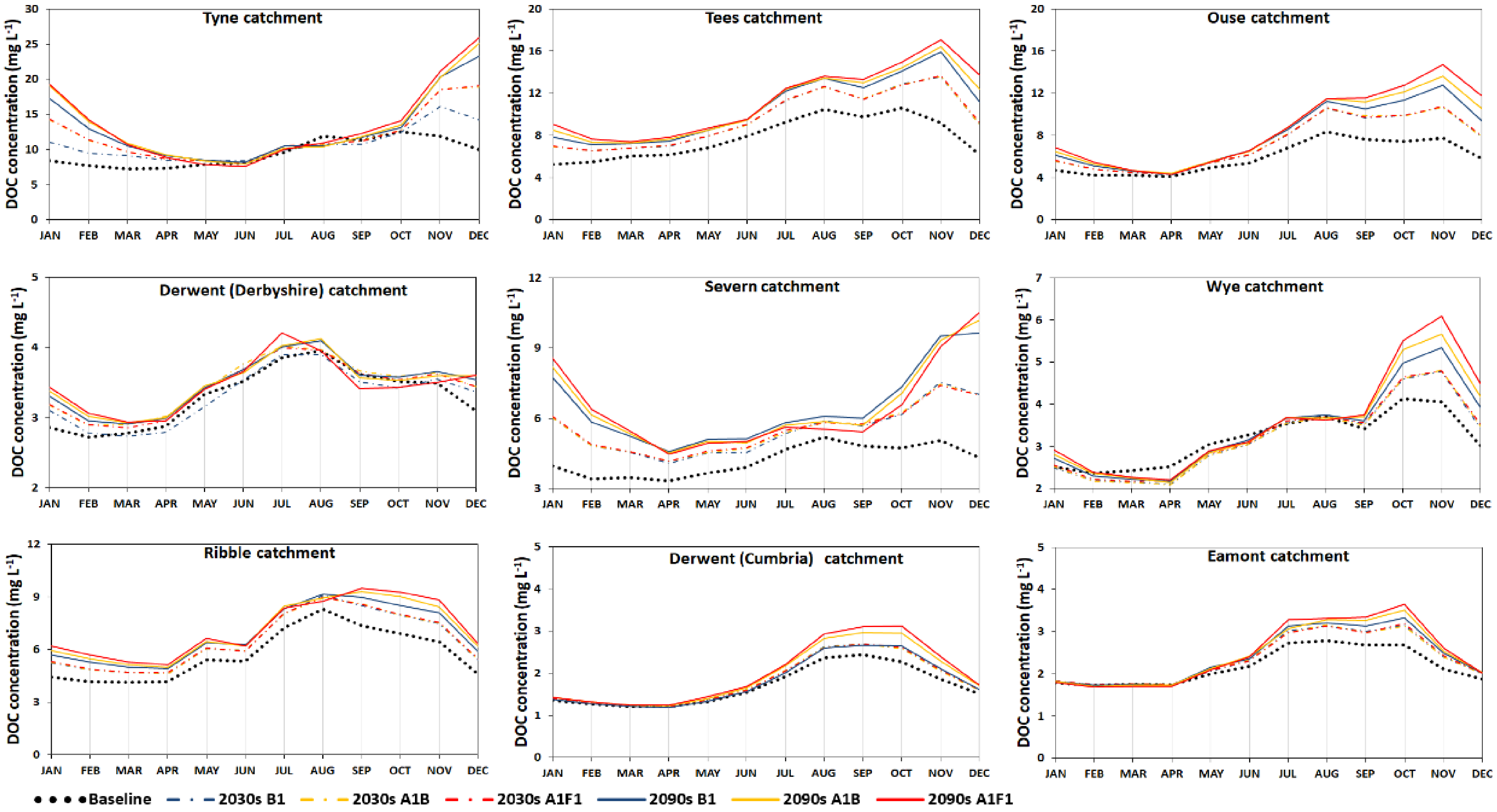

Figure 4.9 Average monthly DOC concentration during the observational baseline period; and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades the 2030s and 2090s.

The simulated effects of future climate change upon annual DOC fluxes are more modest than those for DOC concentrations. The Severn, Tees and Ribble catchments are projected to experience increased DOC flux, while the Wye, Derwent (Derbyshire) and Eamont catchments are projected to experience reduced DOC flux, despite increased DOC concentrations. The simulations indicate no significant change (less than 5 %) in DOC flux for the Tyne, Derwent (Cumbria), and Ouse catchments compared to the baseline period (Figure 4.10).

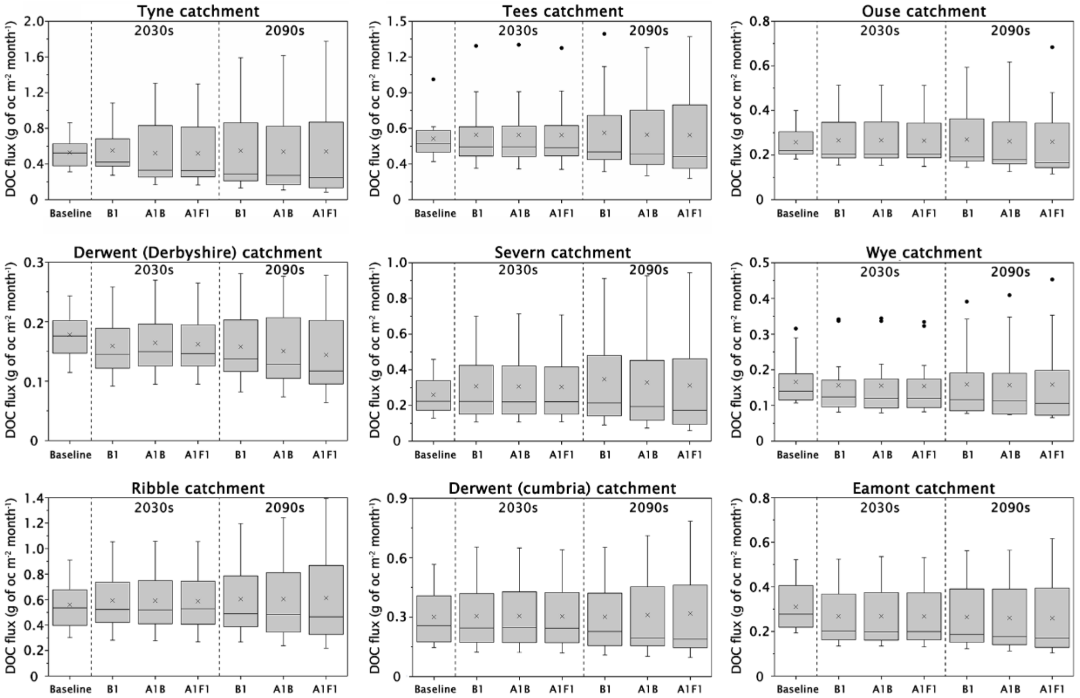

Figure 4.10 Distributions of average DOC flux for each site during the baseline observational period and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades the 2030s and 2090s. Box heights represent upper and lower quartiles of DOC flux; centerlines represent medians; crosses represent means; whiskers extend to values up to 1.5 times the interquartile range beyond the quartiles; filled black circles represent remaining values.

4.3.3 Projected seasonal variability of discharge and DOC

Projected changes in the seasonal patterns of DOC concentrations are of more significance than the annual means, with likely important consequences for both water treatment costs and aquatic ecology. This study finds increasing seasonal variability in DOC concentrations in all nine catchments under future scenarios, with large peaks in DOC concentration when high-flow (wet) months follow a sequence of low flow (dry) months. The projected changes in future sulphate deposition for the 2030s and 2090s contain inter-annual variability, but contain no intra-annual (seasonal) variability (see Methods, above). The temperature and precipitation scenarios this study used to drive models, on the other hand, contain both inter- and intra-annual variability. The simulations project that DOC concentrations in the 2090s will have greater seasonal variability than in either the 2030s or the baseline period (Figure 4.9, Table F.4 and Table F.5) are therefore attributable to the increasing seasonality of precipitation and temperature (Figure G.1 and G.2).Therefore, this study proposes that the large projected decrease in sulphate deposition (36 % of the baseline average during the 2030s; 18 % during 2090s) will be an important driver of the overall change in mean annual DOC concentrations, but that the changes in precipitation and temperature will drive altered seasonality of DOC concentrations. This is consistent with previous studies suggesting that the majority of the increase in DOC concentrations over the past 2-3 decades was associated with the decline in atmospheric sulphate deposition while climate change was likely to result in only modest increases in DOC concentrations in similar catchments in the UK and Norway (Futter et al. 2009; Laudon et al. 2012).

The simulations project a wide and seasonally variable range of future discharge regimes (Figure 4.11). Most of the greatest monthly discharges are projected to occur between October and March, while discharge between April and September is projected to be the lowest and the least variable. With respect to the baseline period, April to September will be the annual period with the largest reduction in discharge as compared with October to March, in which only small changes are projected. As with discharge, the simulations project increased seasonal variability of total DOC flux from all nine catchments from the baseline period to the 2030s, and further increases in seasonality to the 2090s (Figure 4.12). Most of the greatest increases in monthly DOC flux are projected to occur between October and March, while these increases seem likely to be largely counterbalanced by the significant decreases during summer and autumn. Therefore, the simulated effects of future climate change upon annual DOC fluxes are more modest than those for DOC concentrations.

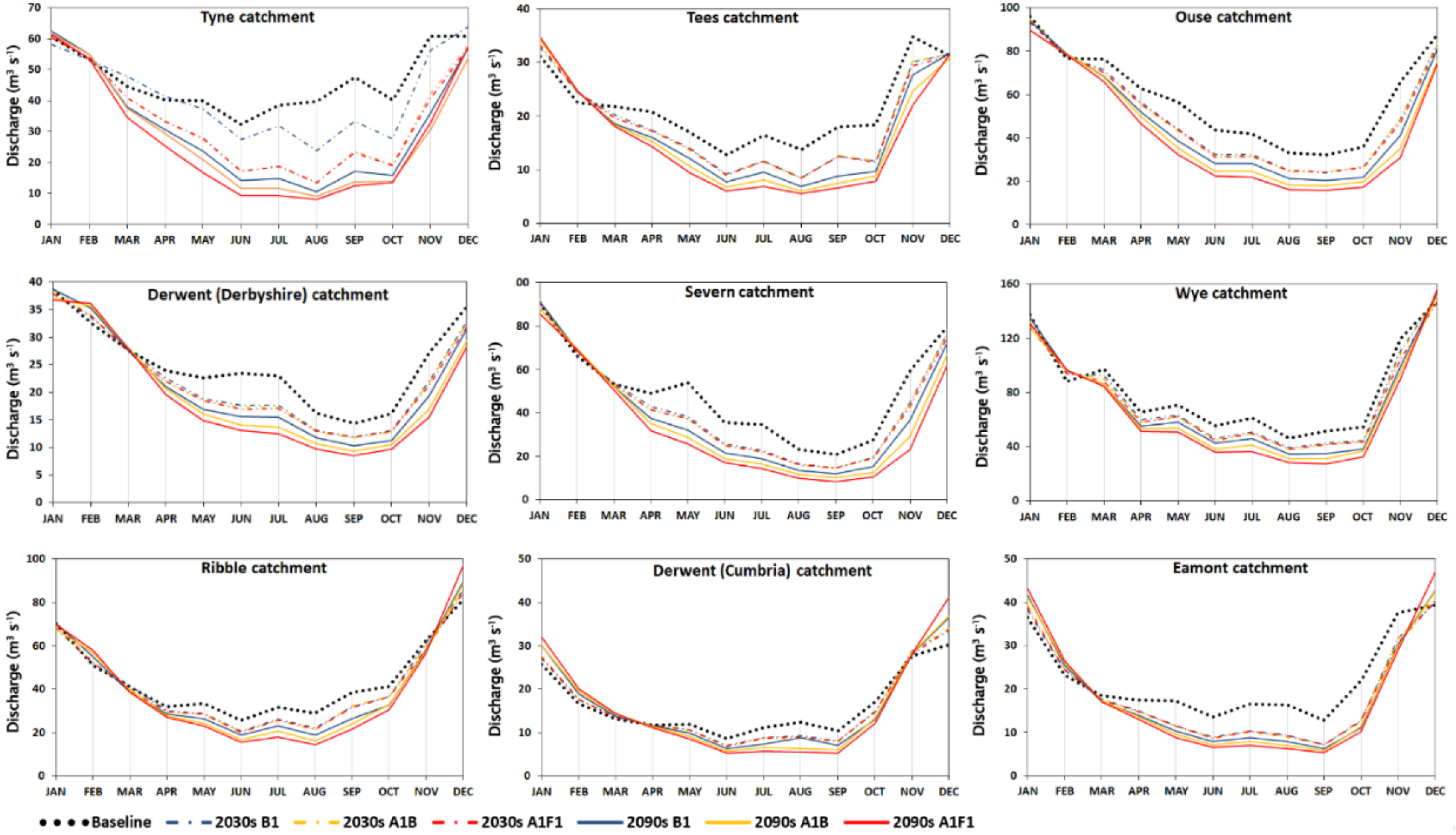

Figure 4.11 Average monthly discharge during the observational baseline period; and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades 2030s and 2090s.

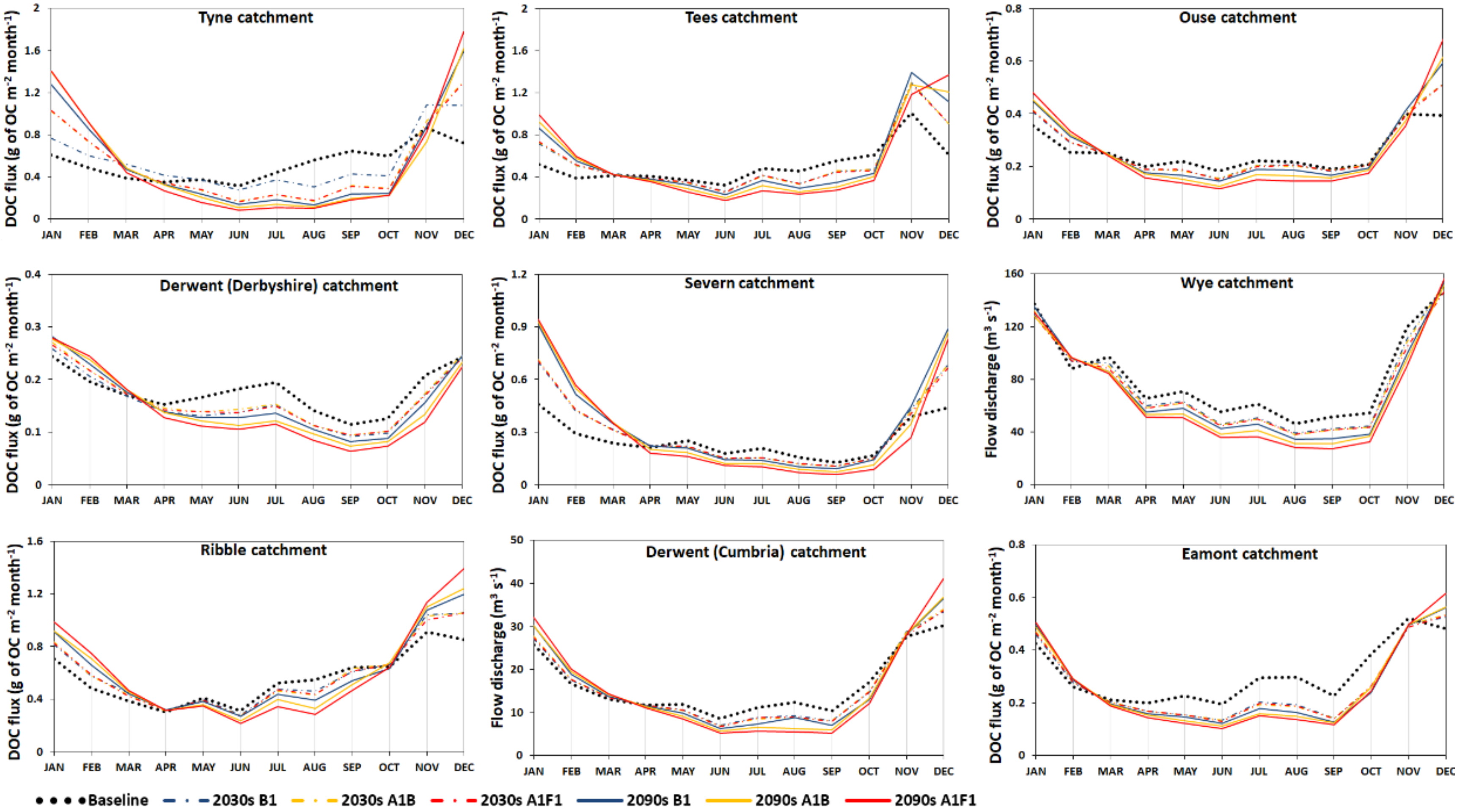

Figure 4.12 Average monthly DOC flux during the observational baseline period; and under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades the 2030s and 2090s.

4.3.4 Implications for water security and carbon budgets

Climate-induced changes to DOC dynamics are likely to threaten regional water security without the increased operational and capital investments to improve DOC removal. Large increases (by as much as a factor of 1.6) in DOC concentration in the 2090s compared to the baseline period are projected in the autumn and winter, a time when DOC concentrations are already high in the baseline datasets. It is at this time of year that water treatment works are already operating at peak DOC removal capacity due to high DOC concentrations. Moreover, there will not only be an increase in DOC concentrations, but also an increasing range and variability of DOC concentrations, which relate to the consequent increase in organic matter solubility (Evans et al. 2006; Hytteborn et al. 2015; Ledesma et al. 2016). The cost of treating DOC in potable water is composed of operational and capital investments. The operational costs include chemical costs of coagulants, increased energy use, staffing and sludge removal. When water DOC-related colour peaks become too severe, the capacity of water treatment facilities is exceeded, new technologies are required, and therefore water companies have to invest in capital for every new treatment plant. The large increases in DOC concentrations in these and other peatland-derived drinking water supply catchments in the coming decades will have important consequences for water treatment infrastructure and would likely require large capital investment to maintain safe drinking water.

Future river discharge in key UK peat-fed drinking water supply catchments is projected to decrease under climate change, which is likely to contribute to increased risk to the water supply. Large decreases in discharges are projected for April to September in the future, periods when discharges are already relatively low. This could also result in water security problems especially since climate change is likely to drive up the demand for water alongside population growth.

Furthermore, in contrast with increased DOC concentrations, median values of total DOC flux are projected to have decreased in the 2090s compared to the baseline. This may have implications for aquatic ecosystems that process DOC. The declining DOC flux in some catchments also suggests that, relative to DOC losses via surface water runoff, gas losses from the terrestrial compartment may become an even more important component of the UK peatland carbon balance in the future. However, peat erosion in the UK has previously been predicted to increase under future climate change, with enhanced losses of particulate organic carbon to the fluvial system (Li et al.

2017). The fate of this particulate carbon is unclear, but work to date suggests around half is trapped in reservoirs or is transported to estuaries, and the rest may be processed to DOC or gas en route (Palmer et al. 2016). Thus, sediment loads, driven by peatland degradation under climate change, may provide both a costly treatment problem related to sediment removal and also provide a future in-stream DOC source that will compound further our predicted increases in DOC concentrations in the future.

4.4 Conclusions

This study is the first to model DOC dynamics in the UK's key peat-fed drinking water supply catchments under future climate and sulphate deposition changes. In summary, taken across all scenarios, annual mean DOC concentrations in peatland-derived potable water will increase while annual mean discharge will decrease. Projected changes in the seasonality of DOC dynamics are important, and projected variability of discharge, DOC concentration and DOC flux are higher in the 2090s compared with that in the 2030s in all catchments, and greater in high GHG emission scenarios than in low GHG scenarios.

Some of the estimates of increasing future DOC concentration and decreasing discharge may be conservative since peatlands are potentially sensitive to human management interventions, but these have not been modelled herein. Most commonly, these interventions (e.g. drainage, overgrazing, afforestation, prescribed burning) change the structural and biological environment of peatlands, damage peat-forming vegetation, potentially leading to increased DOC concentrations and decreased overland flow (Holden et al., 2007). Conservation management and ecological restoration of peatlands to make them more resilient to climate change (e.g. by blocking drainage ditches to maintain shallow water tables (Armstrong et al., 2010)) may be a relatively low cost approach to reducing DOC concentrations in the aquatic compartment as compared with capital and operational investment of DOC treatment and removal in drinking water facilities (Martin-Ortega et al., 2014). However, this cannot be relied upon given the large scale increases in DOC concentrations suggested by simulations of this study, particularly in autumn and winter months. Thus a dual approach will be required to ensure the future security of peatland-derived drinking water in the UK and other similar areas worldwide, involving both more efficient water treatment technology and responsible stewardship of peatlands.

Supporting information

Appendix F Supplementary tables for Chapter 4.

Appendix G Supplementary figures for Chapter 4.

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Chapter 5
Discussion and conclusions

5.1 Summary of thesis findings

This thesis has produced an improved global peatland map, PEATMAP, by amalgamating available peatland geospatial information at various levels based on a meta-analysis. PEATMAP was combined with global datasets of human population, surface hydrology, topography and land use to determine global hotspots of peatland-derived potable water use and to estimate the quantity of global potable water that drains from or through peatlands. In turn, simulations were conducted for the most important peat-fed water supply catchments, which were concentrated in the UK. These simulations of DOC dynamics were conducted for a range of 21st-century climate and sulphate-deposition scenarios by using a physically-based hydrological model (PERSiST) and organic carbon model (INCA-C).

In Chapter 2, I used a meta-analysis of geospatial information collated from 20 individual datasets at global, regional and national levels to produce an improved global peatland map. PEATMAP estimates total global peatland area to be 4.23 million km^2, approximately 2.84 % of the world land area. In Chapter 3, I used global peatland, population and hydrometric datasets to identify hotspots where peatlands are crucial for potable water supply. Doing so entailed the development of two new catchment-scale indices: I developed the Peat Population Index (PPI) and Peat Reservoir Index (PRI). The results demonstrated that peat-rich catchments provide approximately 4.22 km^3 yr^{-1} water globally, equivalent to typical consumption of 71.4 million people, and most of these key areas were found to be in the UK and Republic of Ireland, where approximately 85 % of all global drinking water sourced directly from peatlands is consumed. Globally, only 28 % of peatlands that supply drinking water to large populations are pristine or protected. Thus, peatland restoration and protection are urgently needed to support water security. Finally, in Chapter 4, I used the PERSiST and INCA-C models to simulate DOC dynamics in the UK’s most important peat-fed potable supply catchments under a range of 21st-century climate and sulphate-deposition scenarios. The results indicated that DOC concentrations are likely to increase under all future scenarios tested. Increased DOC concentration will be driven mainly by changes in precipitation, temperature and sulphate, while total DOC flux is largely insensitive because it is offset by a projected decrease in river discharge. Many of the findings presented in this thesis represent broad impressions of current patterns and possible future trends. These could inform peatland restoration projects and plans for conservation under climate change. However, further study of some aspects would be required for a complete understanding of the role of peatlands in drinking water supply. The following sections discuss the findings in the context of wider issues, the implications of this project, and identify future research priorities.

5.2 Findings in a broader context of previous work

This research is the first comprehensive study of the role of peatlands in global potable water provision. The main contributions are summarized below:

5.2.1 Refining estimates of global peatland distribution

Detailed, high resolution, accurate and globally consistent mapping of peatlands is a pre-requisite for assessing their current role in ecosystem functions associated with global models, such as global carbon cycling and water provision and projecting future dynamics and feedbacks. However, there has been little recent progress in mapping peatland distribution on a global scale. Normally, peatlands are considered as a type of high organic carbon wetland, thus in previous research, peatland extents have been extracted based on the datasets of soil organic matter density (e.g. Wania et al., 2009) or wetland or inundation extent maps (e.g. Köchy et al., 2015). The first binary map of global peatland distribution was produced by Yu et al. (2010) from a palaeoenvironmental perspective. However, it is only a binary map in vector format without quantitative information for each pixel, and according to Yu et al. (2010), does not include accurate peatland distributions for many regions due to a lack of reliable source data (e.g. Amazonia, central Africa). The data are also not publicly available. Currently available global maps of wetland or inundation extent are of limited utility for producing a global peatland map, especially for the boreal or tropical peatlands. Because most of these wetland maps or inundation extent maps were produced by using remote sensing data or hydrological models, or combinations thereof. Peatlands in the boreal zones which are underlain by permafrost can be underestimated (Matthews, 1989; Melton et al., 2013). As for tropical peatlands, Gumbricht (2015) and Gumbricht et al. (2017) mapped tropical peatland extents as a part of ‘The Global Wetlands Map’, which is by far the highest spatial resolution and most recent tropical and sub-tropical wetland dataset. However, this product is also restricted to the limitation above since it was mapped by combining hydrological modelling and remote sensing. Therefore, although ‘The Global Wetlands Map’ dataset is part of the data sources for tropical peatland extents within PEATMAP, the peatland extents in some regions (e.g. Indonesia and Malaysia) have been refined by official government maps.

Although there are still some inevitable deviations due to the relatively coarse resolution source data and little-known literature in some regions, this thesis produced a global peatland map that combined the best data sources for the world, meaning that PEATMAP is the highest quality and most detailed shapefile map published. Since PEATMAP is composed of shapefiles, it can present the highest spatial resolution for each region, and it could be easily transferred into grid-based formats if necessary. This shapefile-based PEATMAP could be easily integrated into global ecosystem models, climate models, population models or hydrological models to investigate peatlands at a global scale. PEATMAP suggests that in previous global peatland inventories, tropical peatlands have been underestimated while in the Northern Hemisphere, peatlands have been overestimated. In addition, PEATMAP is freely available in the public domain from the Research Data Leeds Repository (https://doi.org/10.5518/252), and can be easily updated when new peat map data from any region of the world (particularly in the tropics) become available.

5.2.2 Quantifying global peatland-derived potable water

Other than high DOC concentrations, water draining from peatlands is often of relatively good quality and used as water resources by local people (Osaki and Tsuji, 2016; Silvius et al., 1984). Examples of fairly well understood local peatland water resource provision cover high latitude zones with headwater peatlands found to be locally important, especially in densely-populated areas (Fonken, 2014; Salvador et al., 2014; Schittek et al., 2015). However, most of these statements made at a local level about the importance of peatland-derived water resources are lacking appropriate quantification. The most typical case is that many references claim that approximately 70 % of UK’s drinking water comes from upland areas which are dominated by peatlands (Watts et al., 2001), but the contribution of peatlands to this figure has never been verified. Therefore, although peatlands are potentially important water sources for humans, little is known about the role of peatlands in providing global potable water resources. In this thesis, the results suggest that 72.5 % of total storage capacity of UK water-supply reservoirs is peat-fed, and the UK consumes approximately 1.56 km^3 yr^{-1} of peat-fed potable water, equivalent to supporting 28.25 million people or 43.1 % of UK population.

Degradation of peatlands caused by human activities (e.g. exploration, agriculture, drainage) could adversely affect the sustainable provision of clean drinking water. For example, as one of the most notably anthropogenic activities on peatlands, drainage has impacted approximately 0.5 million square kilometres of peatlands globally (Joosten, 2009), often reducing water quality (Evans et al., 2014; Gibson et al., 2009; Holden et al., 2004; Hooijer et al., 2010). Deforested peatlands, which represent a common land-use activity in Europe and Southeast Asia, have been reported to discharge more fluvial organic carbon than intact peat (Haigh, 2006; Moore et al., 2013). However, the global extent of human-induced degradation of peatlands, and the consequences for water provision, are poorly understood.

In this project, I proposed a method to estimate the proportion of streams interacting with peatlands before draining into domestic water sources by combining the peatland map, DEM data and drinking water supply networks. I also developed two new indexes - the Peat Population Index (PPI) and Peat Reservoir Index (PRI). Combined with the Ecosystem-Land Use System (Nachtergaele and Petri, 2011), I determined that only 28% of water-supply peatlands are pristine or protected. This is the first global inventory of peatland water resources, which provides a global context for the importance of peatlands to drinking water supply based on novel approaches, and this is also the first time identifying the global most important drinking water supply peatland catchments which may require conservation action to enhance their resilience to climate change or to protect them from inappropriate land use.

5.2.3 Future DOC dynamics in hotspots of peat-fed drinking water usage

Climate change to 2100 is predicted to cause severe degradation of some peatlands (Li et al., 2017). Evidence in the boreal climate zone, in the temperate climate zone (Clark et al., 2010; Dinsmore et al., 2013; Fenner and Freeman, 2011), and in the tropics (Moore et al., 2011; Rieley et al., 2008) all suggest peatland degradation with rising temperature, enhanced drought frequency and severity potentially increasing peat decomposition, releasing large volumes of aquatic carbon and lowering peatland water quality (Fenner and Freeman, 2011; Field et al., 2014; Worrall et al., 2006). Furthermore, decreasing acid atmospheric deposition is also important in driving DOC export in peatlands (Evans et al., 2006; Monteith et al., 2007). All of these projected changes would appear to indicate increased DOC concentrations in the future, however, little is known about how DOC dynamics in global or hotspot locations for peatland-derived drinking water use will respond.

This thesis is the first study to project DOC dynamics for the UK's key peat-fed drinking water supply catchments under future climate and sulphate deposition changes, suggesting the quality of future (by the 2090s) peatland-derived drinking water would be worse because of the large increases of DOC concentrations. The projected results in this thesis suggest the significant increases in peatland aquatic DOC under future climate changes and also demonstrated that precipitation, temperature, and sulphate deposition have significant effects on DOC concentrations for peatland-derived water, which are consistent with the modelling results of future peatland aquatic trends (e.g. Naden et al., 2010; Aherne et al., 2007). Since the study sites supply 72 % of all peat-derived water consumed in the UK, and 57 % of the global total, these findings can provide benefit-cost evidence for improving conservation and ecological restoration of degraded peatlands not only at the national scale but also globally.

5.3 Limitations of the work

5.3.1 Limitation of PEATMAP

For now, there is no single formal definition of peat that has been accepted worldwide. Also, the minimum peat thickness for a site to be classified as a peatland is different depending on different interest groups (Krankina et al., 2008). Therefore, for PEATMAP, I had to create a combined map from diverse, publicly available data sources with non-uniform definitions of peatlands which depend on local classification schemes, country or the scientific discipline. In addition, to present the details for different data sources as much as possible, PEATMAP does not have a standard spatial resolution-which means every data source remains in their original highest spatial resolution. For example, because the source data were provided as grid cells rather than shape files, the peatlands in Canada, Mongolia, North Korea and the north island of Japan (Hokkaido) were displayed as percentage peatland cover, while others were shown as the individual peatland polygons (Chapter 2). This is an appropriate way to deal with the mixed spatial resolution of data sources, but a dataset with a unique standard spatial resolution would be more welcome in the future, especially for effective inclusion of peatlands into large scale models (Clark et al., 2010). Also, incomplete exploration of some potential forested peatland-rich areas, particularly in the tropics, are not well-presented in the existing peatland maps, including PEATMAP, hence more work is required to map peatlands in these regions.

Another limitation is that PEATMAP could not represent some parts of remote boreal peatlands satisfactorily due to the quality of data sources. For example, parts of Alaska are poorly represented, in particular, the extensive peatlands of the north slope of the Brooks Range Mountains (commonly referred to colloquially as the North Slope). Although there are several studies of peatlands in the North Slope (Jones and Yu, 2010; Mann et al., 2002), all of them are based on the basal peats sampled from the area, and there is no high-quality peatland map for this region available. Peatland maps in the remote Canadian and Alaskan Arctic also have a similar limitation. Also, the individual polygons overestimate peatlands in central and eastern Siberia due to the low spatial resolution there, although they likely indicate areas that contain complexes of smaller peatlands.

5.3.2 Underestimation of peat-fed water supply importance

The estimate of the global volume of potable water supplied by peatlands is a conservative one. I explored the eight catchments identified from the global analysis as PPI hotspots for more detailed study of their water supply and redistribution systems in detail. This involved estimating the proportion of flow accumulation that has interacted with peatlands before draining into streams from which drinking water is abstracted, and the population that use potable water from these peat-influenced sources (all in the appendices to this thesis due to format requirements). The results suggest that peat-fed water consumption in PPI hotspots, added to that supplied from neighbouring PRI catchments, provides a representative estimate of the vast majority of global potable water derived from peatlands. However, this project has still only considered 87.9 % of upland peatlands in the 46 catchments with the greatest PPI (Chapter 3). This is mainly because catchment specific data on potable water supply is considered to be commercially sensitive for the water companies in most of the hotspots (e.g. the UK and the Republic of Ireland), and therefore not generally in the public domain. In addition, because small reservoirs with a storage capacity of fewer than 0.1 km^3 are excluded from the GRanD (Lehner et al., 2011) database, the global PRI value is also a conservative estimate. The exclusion of reservoirs for which domestic water supply is a secondary use also leads to a further small underestimation. Furthermore, this thesis only considered household consumption and will have underestimated peat-fed water supply importance. Other public-supply water which is delivered to users for commercial, industrial, public services or the system losses (e.g. leakage) has not been accounted for in the analysis.

5.3.3 Limitation of data sources for running INCA-C model

In this thesis, future climate change for the UK was derived from the United Kingdom Climate Projection 2009 (UKCP09). Although at the time of writing, the UKCP09 data are the most up-to-date available downscaled climate projections for the UK, these data are soon to be superseded when the first data from United Kingdom Climate Projection 2018 (UKCP18) are released, scheduled for December 2018, followed by finer resolution data in 2019 (only 25 km resolution data available now). The UKCP18 uses new scenarios called Representative Concentration Pathways (RCPs). The RCPs were used in the most recent IPCC report, which will update the existing emissions scenarios used in UKCP09. Future sulphate deposition dynamics were derived from the estimations of Europe from the Atmospheric Chemistry and Climate Model Intercomparison Project since there is no available UK country level sulphate deposition projection data.

5.3.4 Error propagation

It should be noted that errors might propagate throughout the whole thesis since the core results from Chapter 2 to 4 all logically build on one another in sequence. As a prerequisite base dataset, the quality of PEATMAP is crucial to the results for the whole thesis. In Chapter 3, the results of PPI and PRI will be incorrect if there are big errors for some regions in PEATMAP, since these two indices are sensitive to the global population density, peatland distribution, catchment boundaries and river networks. For example, there are potentially peatland areas in PEATMAP which are not very precisely mapped due to the dearth of the high quality available data, non-uniform definitions of peatlands and coarser spatial resolution of data sources in some regions. In addition, as discussed in Section 3.2, there is potentially a MAUP in the PPI result, which may result in different results for PPI hotspots. If PPI or PRI have been calculated incorrectly due to limitations in PEATMAP or the PPI hotspots have been identified incorrectly due to the MAUP, there may be some incorrect calculations of peatland water supply in some important regions, leading in turn to inaccurate global estimation or the hotspots of peatland-derived potable water use. The errors might further propagate to Chapter 4. There may be some other important regions which have not been identified, for which the input data required for modelling are available, and for which DOC dynamics should also be simulated. Similarly, errors in any of the other global datasets used in this thesis, (i.e. population database, hydrography dataset, reservoir and dam database, ecosystem-land use system) will also have propagated through the whole thesis. For example, the small reservoirs with a storage capacity of fewer than 0.1 km^3 which are excluded from the GRanD database may be fed by peat and be used for drinking water supply. If all these peat-fed reservoirs are in a sole catchment, this catchment may be an important peat-fed drinking water supply region, but which has not been identified in this thesis. Furthermore, the identification of drinking water supply peatlands also relies on the resolution of river networks. More peat-fed drinking water supply rivers are potentially be identified based on higher resolution of peatland map and river network data.

5.4 Priorities for future research

In this section, I not only identify some research gaps which this thesis could not answer, but also propose priorities for work that can build on this thesis - the updated global peatland map, novel indices techniques, and the modelling approaches.

5.4.1 Improving the quality of the data source

The accuracy of the peatland maps mainly depends on the quality of source data. For now, the distributions of little-known types of peatland (e.g. tropical peat swamps, permafrost peatland and Andean glacial valley peats) are still unclear. Many of these untraversed peatlands were mapped by remote sensing without comprehensive ground truthing (Krankina et al., 2008; Osaki and Tsuji, 2016), and there may be a large number of tropical peatlands, including beneath dense canopies, which have not been discovered (Osaki and Tsuji, 2016). Therefore, in future studies, more detailed field surveys and better remote sensing techniques will be necessary. In addition, although I applied the most up-to-date and highest quality datasets available, ongoing efforts to improve the quality of global population, land-use and reservoir databases, topography and surface hydrology datasets and climate change scenarios will further refine future estimates of potable water provision from peatlands. For example, the resolution of the Gridded Population of the World Version 4 (GPWv4) is 30 arc-seconds, while higher resolution data such as HydroSHEDS (15 arc-seconds) would be helpful to decrease errors. Moreover, more comprehensive global reservoir records (i.e. small reservoirs with a storage capacity of less than 0.1 km^3) in the global reservoir database will reduce the underestimation of global water provision from peatlands. Furthermore, more open access data would be very welcome in the future. Because of the commercially sensitive nature of water supply data from water companies, only limited data are available, leading to some estimates from this project being highly conservative.

5.4.2 Understanding future peatland water quality pressures under land management

Peatlands globally are under the threat of degradation. About 12 % of all peatlands have been degraded (Joosten, 2009), but only 28 % of water-supply peatlands remain pristine or protected (Chapter 3). Anthropogenic pressures (e.g. drainage, extraction, agriculture and prescribed burning) can affect water quality. Artificial drainage not only influences the properties of the peat, but also the runoff characteristics of outflowing streams by influencing hydraulic conductivity, water storage capacity and flow rates, increased flooding and peat erosion, decrease of water quality and ecosystem destruction (Davies, 2015; Holden et al., 2004; Kopp et al., 2013; Ramchunder et al., 2012; Wosten et al., 2008). Peatland extraction for fuel and horticulture is widespread in parts of Scandinavia, Russia, the Republic of Ireland, and North America, which may profoundly impact hydrological and ecological functions at the regional and local scale (Price and Ketcheson, 2009). About 14-20 % of peatlands in the world are currently used for agriculture and millions of people depend on agriculture on peatlands for herding livestock, forestry, and growing crops (Joosten et al., 2012). Although previous studies suggested no significant difference in DOC between grazed and ungrazed peatlands (e.g. Clay et al., 2009; Worrall et al., 2007a), however, these studies focus on the presence/absence of sheep rather than the direct impact (e.g. consumption and egesta of sheep) and physical impact of sheep (e.g. sheep trampling) (proxy to grazing intensity) (Clay and Worrall, 2013; Worrall and Clay, 2012). It is still poorly understood how grazing affects peatland aquatic DOC, and there are very few relative studies available (e.g. Clay and Worrall, 2013). Cropping will affect the soil surface condition, making the soil surface compacted, and accelerate degradation (Burt and Slattery, 2006). Although artificial drainage accompanied by agriculture activities on peatlands has been suggested to increase peatland aquatic DOC (Holden et al., 2004; Peacock et al., 2015), there is little work explaining the contribution of crop farming alone (excluding artificial drainage) in changing DOC dynamics. Prescribed burning may result in more damage to peat soil, change hydrological functioning, affect fluvial export of DOC (Clay et al., 2010, 2012; Holden et al., 2015; Yallop et al., 2010), and increase the emissions of GHG by affecting the vegetation and acrotelm, and possibly even catotelmic peat (Tian et al., 2008; Wilson et al., 2015). However, in this project, future DOC dynamics of peatland catchments under these anthropogenic pressure factors have not been projected. For now, some conceptual approaches have been proposed to link the anthropogenic pressures with peatland ecosystem functions (e.g. Evans et al., 2014), which would be helpful for quantification of the effects of anthropogenic pressures on peatland water DOC on a large scale. In future, a better incorporation of anthropogenic pressure factors into the model such as drainage, extraction, prescribed burning and restoration would be desirable.

Furthermore, although lots of money is going into peatland restoration, how peatland restoration will affect future DOC processing is still little known. For example, in the UK, numerous projects have been invested in drain blocking, one of the most commonly reported practices used in peatland restoration projects. However, even for this most common restoration practice, the efficacy of the drain blocking is uncertain. It was reported that DOC concentrations and water discolouration could be lower after 10 years from blocked drains in disturbed peatland catchments (Armstrong et al., 2010; Strack et al., 2015). However, drain-blocking may not always result in decreased DOC concentration in the short or even long-term (Peacock et al., 2018; Worrall et al., 2007b). Other techniques such as gully blocking, bare peat stabilisation and restoration logistics have also been applied in peatland restoration projects (Parry et al., 2014). As a result, water table, stream runoff, stream peak flow, DOC, water colour, pH, and water chemistry may be affected by restoration but there is a lack of understanding of the trajectory of these systems after restoration intervention and a lack of strong data on DOC effects (Alderson et al., 2019). It is often still uncertain whether all hydrological and water quality functions will return when degraded peatlands are subject to restoration management due to limited long-term evidence, and in many cases even decades after restoration, the hydrology and water quality is still different to that of nearby intact peatlands (Haapalehto et al., 2011). For example, Alderson et al. (2019) reported for the first time on trajectories of ecosystem services change following the restoration of eroded blanket peatlands mainly in the Peak District National Park, UK. According to Alderson et al. (2019), there is no statistically significant pattern of change in DOC concentrations and fluxes over five years. However, these results were based on a compilation of datasets acquired from multiple restoration projects rather than a single project with similar objectives and project design. Thus, in future, more work over a long-term timescale is needed to understand whether the spatial and temporal variability causes considerable differences in the efficacy of restoration, and how these restoration activities will affect DOC dynamics under future climate change scenarios.

5.4.3 Exploring the role of peatlands in non-potable water supply

As described in Chapter 1, peatlands can be water sources for agriculture, whether the agricultural activities happen on peatlands (e.g. paludiculture) or elsewhere. Although there is no dataset on the contribution of peatlands to industrial water use, water delivered from many peatland catchments was found to be used for hydropower (Chapter 3). However, in this thesis, only the drinking water provision function of peatlands has been investigated. Therefore, more field observations, secondary data collection and methods need to be derived on agricultural and industrial uses of peatland-derived water.

5.4.4 Future work to build on this thesis

Measured runoff and DOC data for peatland catchments are important for calibration and validation for DOC modelling. However, long-term observational data on runoff and DOC from peatlands at catchment scales are rare, and good coverage only exists in some well-studied regions such as North America and Europe. There are important gaps in some peat-rich regions like Southeast Asia, Amazonia and central Africa. Therefore, more long-term field observations on runoff and DOC in peatland catchments are urgently needed although some recent projects have commenced on the collection of runoff and aquatic DOC data for peatlands in these relatively under-studied regions. A study to predict the total future aquatic DOC flux from peatlands globally would be welcome to support projections of the impact of climate change on global carbon cycling. The global peatland catchments which were identified by combining PEATMAP and HydroSHEDS could be used to indicate regions where runoff and DOC data need be collected. Some calibration data are missing (i.e. long-term runoff and DOC concentration) but could be estimated based on *in situ* short-term data by statistical methods or proxies of long-term data from a nearby location with a similar environment. The driving data for modelling (i.e. climate data, sulphate deposition, and land-cover dataset) and future climate change scenarios are all available globally. The INCA-C model has been successfully employed in several boreal and temperate peatlands, but it still needs to be tested in tropical peatlands, thus some necessary modifications of model might be needed.

PEATMAP could also be applied in refining estimates of global peatland carbon stocks. The magnitude of the peatland carbon pool can be obtained by multiplying peat volume by bulk density and percentage carbon content. The data source of peat thickness in different regions could be derived or estimated based on local peatland inventories, and the bulk density and carbon concentration of peats could also be derived from published data (e.g. published papers or global soil database).

A cost-benefit analysis looking at how investment in peatland restoration might offset operational and/or capital costs in the future could be undertaken. More detailed (but often commercially sensitive) water treatment cost data including operational and capital costs from water companies, and the cost of peatland restoration is required. In addition, more research is needed to investigate the discharge and DOC impacts of peatland management practices and climate change. This will equip water companies and policymakers with information to help adapt to environmental change and opportunities that lie ahead.

5.5 Summary

In summary:

(1) I produced an improved amalgamated global peatland map based on a meta-analysis of geospatial information collated from the best available data sources at global, regional and national levels.

(2) The total global peatland area was estimated to be 4.23 million km^2, approximately 2.84 % of the world land area. Previous global peatland inventories are likely to underestimate peat extent in the tropics, and to overestimate it in parts of mid- and high-latitudes of the Northern Hemisphere.

(3) Water supply peatlands provide approximately 4.22 km^3 yr^{-1} of peat-fed drinking water globally, equivalent to total annual consumption by 71.4 million people.

(4) Peatlands play crucial roles in the water security of the UK and the Republic of Ireland, where approximately 85 % of all drinking water delivered directly from peatlands globally is consumed in these countries.

(5) Responsible stewardship of these supply catchments is required since only 28% of water-supply peatlands are pristine or protected globally.

(6) Mean annual DOC concentrations in UK water sources are likely to increase under 21st-century climate and sulphate deposition scenarios, by as much as 53.4 % for the highest emissions scenario.

(7) Large increases in DOC concentration are projected in future autumn and winter seasons, periods when DOC concentrations are already high in the baseline datasets.

(8) Large decreases in mean discharge are projected for April to September, periods when discharge is already low.

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Appendix A
Supplementary notes for Chapter 2 (Paper I)

In this appendix, details of the data sources used to produce PEATMAP are provided. These sources were selected based on methods described in the main paper. The inventory of data sources used to produce PEATMAP is shown in Table A.1, and the geographic differences in the period (date) of most recent revision of these data sources is shown in Figure A.1, the spatial resolution distribution of these data sources are shown in Figure A.2, and the map scale distribution of these data sources is shown in Figure A.3.

Table A.1 Inventory of data sources used to produce PEATMAP.

Region	Reference	Map scale/ nominal resolution (spatial resolution)	Period (date) of most recent revision	Notes
Northern Peatlands (>30°N latitude)				
United Kingdom	British Geological Survey (2013)	1: 625,000	2003-2010	Peat feature from Surficial Deposits of DiGMapGB-625
	Morton et al. (2011)	25 m	2007	'Bog' and 'Fen, Marsh and Swamp' layers of UK Land Cover Map (LCM) 2007
Ireland	Teagasc (2014)	1: 250,000	2002-2009	Using peatland features
Finland	Geological Survey of Finland (2010)	1: 200,000	2002-2009	Using peatland features
Sweden	Geological Survey of Sweden (2009)	1: 1,000,000	Around 1994	Using peatland features extracted from quaternary deposits map
Other European regions	Hiederer (2013)	1 km	2000-2006	'Peat' attribute maps from 'European Soil Database (ESDB) Derived data'

Region	Reference	Map scale/ nominal resolution (spatial resolution)	Period (date) of most recent revision	Notes
Western Siberia	Sheng (2009)	1: 1,000,000	1999-2001	West Siberia peatland features
Asian Russia (Except Western Siberia)	Stolbovoi and McCallum (2002)	1: 2,500,000	1990s	Using (1) Bogs with deep peat (>50 cm) and (2) Swamps with shallow peat (30-50 cm) features from Russia Wetland Database
Canada	Tarnocai et al. (2011)	1: 6,500,000	2011	Using Bog, Fen and Swamp features with percentage
United States	Soil Survey Staff (2012)	1: 1,000,000 in Alaska and 1: 250,000 in other regions	1999-2005	Using histosols order and gelisol-histel sub-order layers of STATSGO2
China	Ma et al. (2015)	1 km	2000	Using bogs, fens, swamps and marshes that are non-saline and which excludes lakes or river wetlands
Tropical Peatlands				
Indonesia	Ritung et al. (2011)	1: 250,000	2005-2010	Peat feature from ‘Indonesia Peat Lands’ dataset
Malaysia	Wetlands International (2010)	1: 50,000	2002-2009	Peat feature from ‘Malaysia Peat Lands’ dataset
Central Congo Basin	Dargie et al. (2017)	50 m	2009-2010	Peat swamp forest feature

Region	**Reference**	**Map scale/ nominal resolution (spatial resolution)**	**Period (date) of most recent revision**	**Notes**
Other regions in 38° N to 56° S; 161° E to 117° W	Gumbricht (2015)	236 m	2011	‘Peat’ attribute layers derived from ‘Tropical Wetland Distribution (38° N to 56° S; 161° E to 117° W)’
Southern Peatlands (>30 °S latitude)				
Australia (Except Tasmania)	Environment Australia (2015)	1: 500,000	2001-2010	Peatland features from Directory of Important Wetlands in Australia
Tasmania	Department of Primary Industries and Water (2013)	1: 25,000	2013	MBU, MBW, MSW, MSP, MRR features from ‘Moorland, Sedge land, Rush land and Peatland’ class
New Zealand	MFE (2013)	1: 50,000	2008	Current extent feature of peatlands from wetland typology
Other regions (i.e. Hokkaido, Mongolia, and North Korea)	FAO/IIASA/ISRIC/ISSCAS/JRC (2012)	30 arc-second (c. 1 km at the equator)	1997	Using histosol features from HWSD v1.2 with a percentage

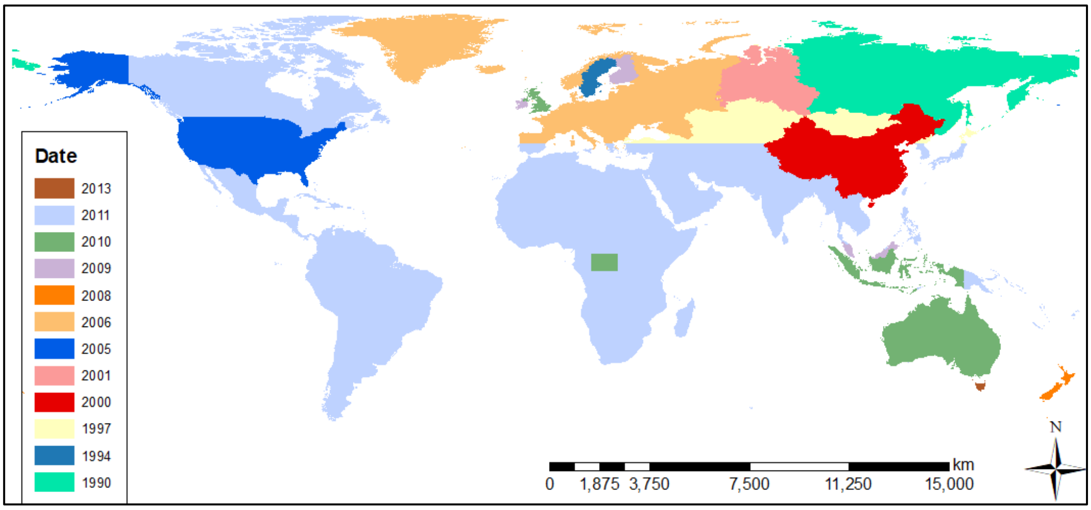

Figure A.1 The period (date) of the most recent revision of data sources used to produce PEATMAP.

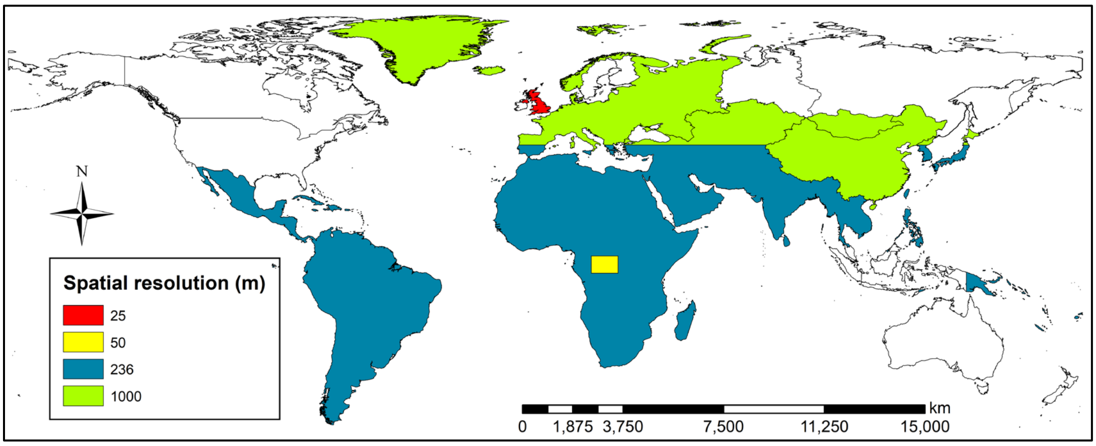

Figure A.2 Distribution of the spatial resolution of data sources used to produce PEATMAP. Blanks indicate areas where there are no suitable map data with a spatial resolution.

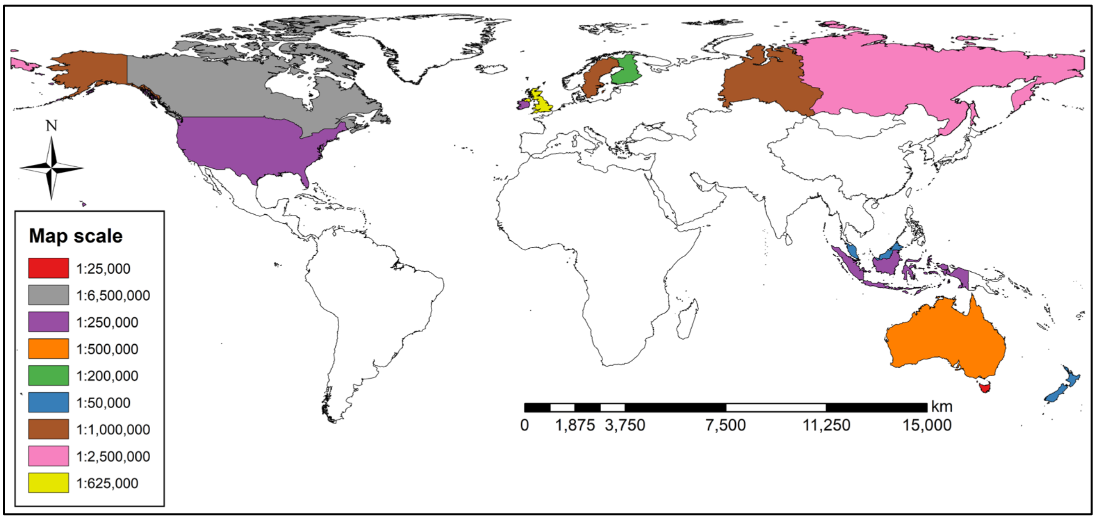

Figure A.3 Map scale distribution of data sources used to produce PEATMAP. Blanks indicate areas where there are no suitable map data with a data scale.

A.1 Northern Peatlands (>30°N latitude)

The UK peatland maps in this study have involved combining peat feature from DiGMapGB-625 with the ‘Bog’ and ‘Fen, Marsh and Swamp’ layers of UK Land Cover Map (LCM) 2007 (Morton et al., 2011).

The DiGMapGB-625 Surficial Deposits dataset is a freely available superficial theme of the Digital Geological Map of Great Britain at 1: 625,000 by the British Geological Survey. The DiGMapGB-625 Surficial Deposits dataset was compiled from the latest available 1: 50,000 data of England and Wales, Scotland and the Isle of Man and the 1: 250,000 published Quaternary map of Northern Ireland. The most recent source data for DiGMapGB-50 was resurveyed in 2003 and published in 2010. The survey of superficial geological deposits in the UK recognised the occurrence of peat deposits extending to at least 1 m below the ground surface (McMillan and Powell, 1999).

The surficial peat deposits that occur entirely within 1 m of the ground surface are not included in DiGMapGB-625 as superficial geology mapping was intended to show material underlying the modern soil profile (Joint Nature Conservation Committee, 2011; Smith et al., 2013). Thus, for shallower peatlands, LCM 2007 was used. It is a parcel-based classification of 23 types of British land cover as part of the UK Biodiversity Action Plan (BAP) Broad Habitats. The spatial resolution of LCM 2007 is 25 m and source data were collected around 2007. The UK LCM 2007 provides the spatial distribution of ‘Bog’ and ‘Fen, Marsh and Swamp’ based on the habitat and vegetation information and provides good information on surficial peatland extent (e.g. blanket bog or raised bog plant communities associated with peats).

The Irish National Soils Map (Teagasc, 2014) is one part of the Irish Soil Information System project which provides a national association soil map for Ireland at a scale of 1: 250,000 by adopting a combined methodology of utilising novel geo-statistical predicted mapping techniques in tandem with traditional soil survey applications during the period 2002-2009.

Superficial deposits of Finland 1: 200,000 (sediment polygon) was produced by Geological Survey of Finland (2010) which contains data produced from the whole of Finland during the period 2002-2009 at a scale of 1: 200,000.

The Swedish Quaternary Deposits map is produced by Geological Survey of Sweden (2009) and provides peat coverage for Sweden at 1: 1,000,000 and reflects the soil information from around 1994.

For other parts of Europe, the ‘peat’ layer from the European Soil Database Derived data with a raster resolution of 1 km was used, which was last updated in the period 2000-2006 (Hiederer, 2013). The classification of peat was performed on the basis of the soil clay and organic carbon content as found in the Soil Geographical Database of Eurasia v 4.0. Therefore, only for regions where an updated peatland map was unavailable, the PEATMAP data were derived from European Soil Database Derived data.

The Asian Russia peatland map was compiled from two datasets - Western Siberia peatland GIS Data Collection (Sheng, 2009) and Russia Wetland Database (Stolbovoi and McCallum, 2002). Detailed physical characteristics of 9,691 individual peatlands (patches) in the 1: 1,000,000 Western Siberia peatland GIS Data Collection were obtained from previously unpublished Russian field and ancillary map data, previously published depth measurements, and field depth and core measurements were taken throughout the region during field campaigns in 1999-2001 and published in 2009. The Russian Wetland Classification Shapefile was generalised from the standard 1: 2,500,000 soil map of Russia and reflected the soil situation in the 1990s.

The Peatlands of Canada in Geological Survey of Canada Open File 6561 (Tarnocai et al., 2011) was developed in 2011 by updating the 2005 version of the database using new spatial and site data, together with updated information from the peatland component of the Soil Organic Carbon Database. Peatlands are classified as land surfaces containing more than 40 cm of peat accumulation on which poorly-drained organic soils develop. The map scale of Peatlands of Canada is 1: 6,500,000 and reference year of source data last revision is 2011. The Bog, Fen and Bog/Fen features in this dataset were used to produce PEATMAP.

STATSGO2 is a broad-based inventory of soils at 1: 250,000 for continental U.S., Hawaii, Puerto Rico and the Virgin Islands and at 1: 1,000,000 in Alaska. It uses the United States soil classification system - Soil Taxonomy. In the United States soil classification system - Soil Taxonomy (Soil Survey Staff, 2012), soils where the surface organic layer is more than 40 cm thick have been classified as histosols, while permafrost-affected organic soils (i.e. permafrost peats) are classified as the histels suborder in the gelisols order. Therefore, the peatlands in the United States were derived from the histosols and gelisol-histel layers of the Digital General Soil Map of the United States. The source materials of STATSGO2 include multiple soil survey publications from the United States, the USGS, and the 2005 National Soil Information System (NASIS) data base from NRCS.

The source data of China's peatland distribution was derived from the Hybrid Palustrine Wetland Map of China (HPWMC) by Ma et al. (2015). The HPWMC is a hybrid map of 1 km spatial resolution reflecting bogs, fens, swamps and marshes that are non-saline and which are not lakes or rivers. HPWMC was mapped based on seven existing datasets including the wetland database of the Chinese Academy of Sciences; the wetland database of Beijing Forestry University; the wetland database of Chinese Land Use; the Global Lake and Wetlands Database; the Chinese wetland census dataset; historical temperature and precipitation datasets; and 1 km resolution DEM. The reference year of the last revision is 2000. These datasets were processed by (1) ranking available datasets, (2) ranking pixels and (3) allocating the statistics of palustrine wetland area for each province reported in the Chinese wetland census database to pixels. First, the five datasets were ranked based on their data quality. The most important criterion is relevance, followed by the spatial resolution. When all five maps indicated a pixel as a palustrine wetland, then it was given the highest rank of 1. If four maps showed a pixel as a palustrine wetland (four yes [Y] combinations), then they created the rank based on the priority orders of these four maps. A similar approach was applied for 3Y, 2Y and 1Y combinations. It should be noted that the data processing method by Ma et al. (2015) is only suitable for the case when all components of the inventory (e.g. census database) are available. For example, in Ma et al. (2015), the census data for each province are the most accurate sources of palustrine wetland area because this wetland inventory was produced with greatest rigour (State Forestry Administration, P. R. C., 2004). Therefore, due to the lack of a rigorous global peatland inventory, the method of ranking the pixels used in Ma et al. (2015) is unable to be used in this thesis. In this thesis, all the available datasets have been ranked to select the best data sources for PEATMAP. Although similar to Ma et al. (2015), the most important criterion is relevance, followed by the spatial resolution. An important criterion of 'age of data sources' which has not been considered by Ma et al. (2015) was also taken into account in this thesis.

The HPWMC has been validated showing that it can reproduce high fidelity distributions of peatland in China according to the national statistics database, although there still could be some undiscovered peatlands have been omitted and some peatlands may have been incorrectly classed (i.e. small error of omission, but unknown error of commission). It should be noted that palustrine wetland refers to non-tidal marshes, peat swamps, bogs, and fens (Ramsar Convention Secretariat, 2013), which means some non-peatlands may be incorporated in the palustrine map (i.e. non-tidal marshes). However, there are approximately 11,343 km^2 of marshes in China (Zhang et al., 2014), only accounting for 8.28 % of total Chinese palustrine wetland area. The area of non-tidal marshes should be much less than the total area of marsh, therefore, HPWMC could be used to determine the peatland distribution in China.

A.2 Tropical Peatlands

The Indonesia peatlands map at a scale of 1: 250,000 published by Indonesia Ministry of Agriculture (Ritung et al., 2011) is the official government map of peatlands in Indonesia. It is based on several preceding peatland and soil maps of Indonesia, including the Land Resource Evaluation and Planning Project data (LREP, 1999), Land Form Classification Maps produced by Regional Planning Program for Transmigration (RePPProT, 1989), Wetlands International peatland map (Wahyunto et al., 2006; Wahyunto and Subagjo, 2003; Wahyunto and Suparto, 2004) and data from several more recent updated regional land and soil surveys in 2005-2010 (Haryono and Ritung, 2011).

The Malaysia Peat Lands map was released by Wetlands International (2010) to assess the status, extent, distribution, and conservation needs for peatlands in Malaysia by overlaying 2009 satellite imagery (Landsat Thematic Mapper, scale 1: 50,000) on a 2002 map of land use provided by Department of Agriculture. Ground data were collected in sample sites throughout the peninsular to assess the local extent and condition of peat soils.

Peatland extents in the Central Congo Basin were derived from Dargie et al. (2017). This GIS file was produced by combining radar backscatter, optical data and ground data. The spatial resolution of these data is 50 m and the latest date of acquisition data of remote-sensing products used in mapping peatland extent is 2010.

The Tropical and Sub-Tropical Wetland Distribution dataset by Gumbricht (2015) is one part of The Global Wetlands Map which was produced by the Sustainable Wetlands Adaptation and Mitigation Program (SWAMP). This dataset shows a distribution of wetland that covers the tropics and subtropics (38° N to 56° S; 161° E to 117° W), excluding small islands. It is by far the highest spatial resolution and most recent tropical and sub-tropical wetland dataset. It was mapped at 236 m spatial resolution by combining a hydrological model and annual time series of satellite-derived estimates of soil moisture to represent water flow and surface wetness that are then combined with geomorphological data, and the source data collection period was around 2011.

A.3 Southern Peatlands (>30 °S latitude)

Directory of Important Wetlands in Australia Spatial Database is a polygon coverage dataset produced by Environment Australia (2015) that presents the different types of wetland (e.g. marsh, swamp, peatland) boundaries and locations in Australia on a scale of 1: 500,000 from 2001 to 2010. We also used the Tasmanian Vegetation dataset produced by Tasmanian Resource Management and Conservation Division (Department of Primary Industries and Water, 2013) which depicts the extent of more than 150 vegetation communities, including those representing peatlands at 1: 25,000 spatial coverage. TASVEG (Tasmania's vegetation) is continually revised and updated via photographic and satellite image interpretation and is verified in the field where possible. The reference year of source data last revision is 2013.

The Current Wetland Extent 2013 from The Ministry for the Environment and Statistics New Zealand (Ministry for the Environment and Statistics New Zealand, 2013) provides the current extent of seven classes of wetlands of New Zealand at 1: 50,000 by using 26 Landsat ETM+ satellite imagery in 2008 and wetland point, and polygon data collated from surveys, field work or photo-interpretation held by local and central government.

A.4 Harmonized World Soil Database (HWSD) v1.2

For Mongolia, North Korea and the north island of Japan (Hokkaido) (South Island peatlands were derived from Tropical and Sub-Tropical Wetland Distribution dataset which cover 38° N to 56° S and 161° E to 117° W), where a high-quality peatland spatial dataset is unavailable, the peatland extents were determined from the histosol maps derived from HWSD v1.2. The HWSD v1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012) has a nominal resolution of 30 arc-seconds on the ground (corresponding approximately to 1 × 1 km at the equator). The raster database contains more than 40 years of soil information. A map of histosols was derived from HWSD according to the FAO-74 and/or the FAO-90 soil classification. Five source databases (Table A. 2) were used to compile version 1.2 of HWSD. The period of most recent revision according to the source dating protocol is the 1980s which is when the second national soil survey of China was launched. This study used the date consistent with the authors' definition for histosols as the date of most recent revision.

Table A.2 Source databases of HWSD v1.2.

Source database	Data source
Soil Map of the World	The Digitized Soil Map of the World Including Derived Soil Properties (version 3.5) (FAO, 1995, 2003) The FAO-UNESCO Soil Map of the World. Legend and 9 volumes. UNESCO, Paris (FAO, 1971-1981)
SOTER regional studies	Soil and terrain database for north-eastern Africa and Crop production zones (FAO, IGADD/ Italian Cooperation, 1998) Soil and Terrain database for north and central Eurasia at 1: 5 million scale (FAO/IIASA/Dokuchaiev Institute/Academia Sinica, 1999) Soil and terrain digital database for Latin America and the Caribbean at 1: 5 Million scale (FAO/UNEP/ISRIC/CIP, 1998) Soil and Terrain Database, Land Degradation Status and Soil Vulnerability Assessment for Central and Eastern Europe (1: 2,500,000) (FAO/ISRIC, 2000) Soil and Terrain Database for Southern Africa (FAO/ISRIC, 2003) SOTER-based soil parameter estimates for Central Africa-DR of Congo, Burundi and Rwanda (SOTWIScaf, version 1.0) (Batjes, 2007) SOTER parameter estimates for Senegal and The Gambia derived from SOTER and WISE (SOTWIS-Senegal, version 1.0) (Batjes, 2008) Soil property estimates for Tunisia derived from SOTER and WISE. (SOTWIS-Tunisia, version 1.0) (Batjes, 2010)
The European Soil Database	European Soil Bureau European Soil Database (v. 2.0) (Panagos et al., 2012)
Northern Circumpolar Soil Map and database	Datasets with dominant soil characteristics at a scale of 1: 10,000,000 (Tarnocai et al., 2002)
The Soil Map of China 1: 1 Million scale	The Soil Map of China based on data from the office for the Second National Soil Survey of China and Institute of Soil Science in Nanjing (Shi et al., 2004)
	Version 2.0 of the WISE database (Batjes et al, 1997; Batjes, 2002)

Source database	Data source
Soil parameter estimates based on World Inventory of Soil Emission Potential (WISE) database	SOTWIS (Batjes, 2007; Van Engelen et al., 2005)

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Batjes, N.H. 2007. SOTER-based soil parameter estimates for Central Africa-DR of Congo, Burundi and Rwanda (SOTWIScaf, version 1.0) ISRIC - World Soil Information, Wageningen.

Batjes, N.H. 2008. SOTER parameter estimates for Senegal and The Gambia derived from SOTER and WISE (SOTWIS-Senegal, version 1.0) ISRIC - World Soil Information, Wageningen.

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Appendix B
Supplementary figures for Chapter 2 (Paper I)

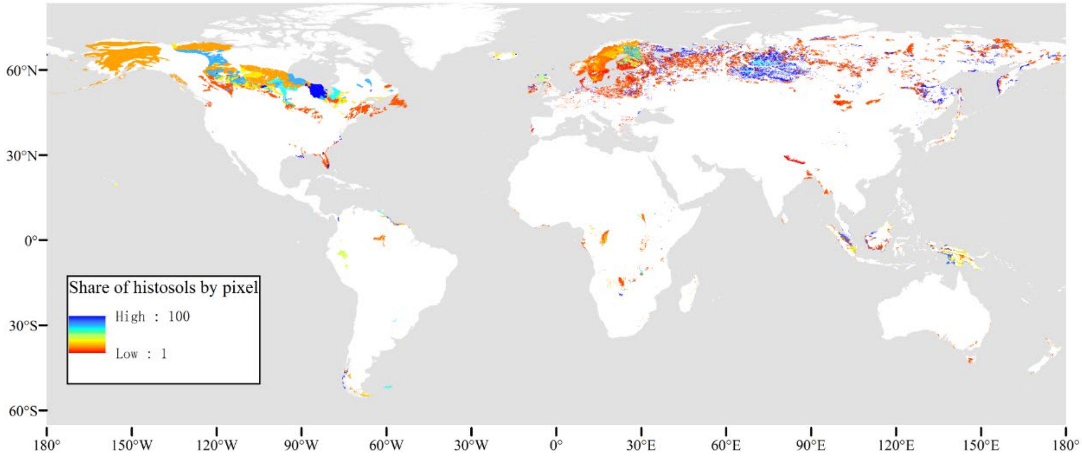

Figure B.1 Global distribution of histosols and share by pixel (in percentage) derived from HWSD v1.2 (Köchy, et al., 2015).

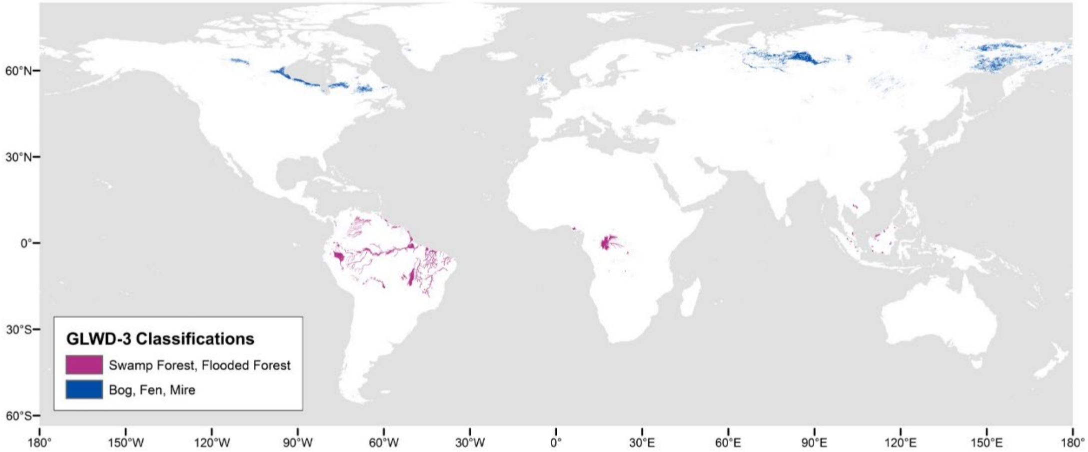

Figure B.2 Global 'Bog, Fen, Mire' and 'Swamp Forest, Flooded Forest' distribution derived from GLWD-3.

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Appendix C
Supplementary figures for Chapter 3 (Paper II)

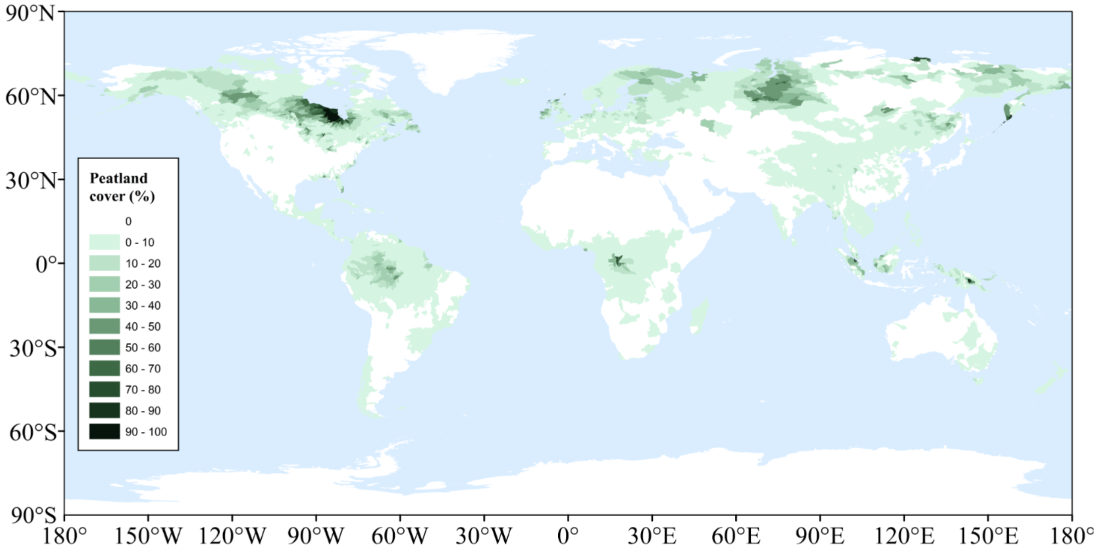

Figure C.1 Global peatland distribution as a percentage cover of each catchment, calculated based on a recent global inventory of peatland distribution - PEATMAP, and sub-basin catchment boundaries according to the FAO's AQUASTAT database.

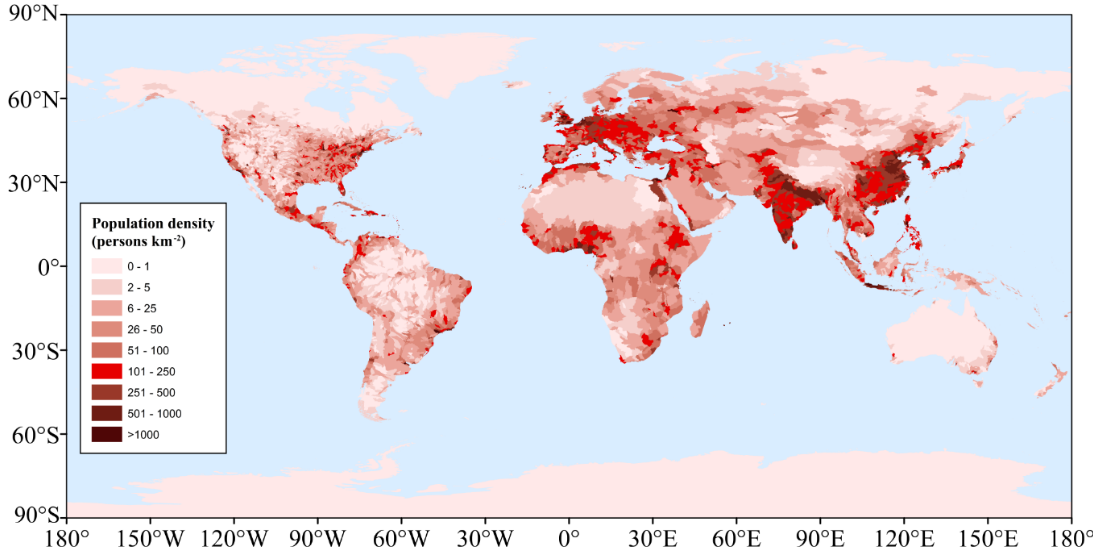

Figure C.2 Population density distribution partitioned using the same sub-catchment topographic boundaries as those in Figure C.1. Scale of underlying population database is 30 arc-seconds (c. 1 km at the equator), based on the 2010 population grid derived from the Gridded Population of the World Version 4 (GPWv4) database and the sub-basin catchment boundaries dataset.

Appendix D
Supplementary tables for Chapter 3 (Paper II)

Table D.1 (part I) Information of global PRI catchments. The entire table can be found by the link: https://doi.org/10.1038/s41893-018-0064-6 or https://static-content.springer.com/esm/art%3A10.1038%2Fs41893-018-0064-6/MediaObjects/41893_2018_64_MOESM2_ESM.xlsx

Reservoir Name	**Latitude (Geographic Coordinates Degrees)**	**Longitude (Geographic Coordinates Degrees)**	**Catchment**	**Total national potable water consumption (litres per person per day)**	**Country**	**Continent**
Backwater	56.7163	-3.2221	Isla / Dean	151 (Eurostat, 2015)	United Kingdom	Europe
Carron Valley	56.0463	-4.1313	Endrick Water			
Loch Arklet	56.2488	-4.6529				
Glen Finglas	56.2413	-4.3738	Teith			
Loch Venacher	56.2288	-4.2688				
Katrine	56.2329	-4.4413				
Megget	55.4954	-3.2538	Tweed			
Talla	55.4913	-3.4163				
Camps	55.4871	-3.5812	Clyde			
Daer	55.3646	-3.6138				
Bradan	55.2504	-4.4662	Water of Girvan / Stinchar			
Kielder Reservoir	55.1871	-2.4621	Tyne			
Derwent (Tees)	54.8621	-1.9621				
Cow Green	54.6579	-2.2913	Tees			
Selset	54.5871	-2.1288				Europe

Reservoir Name	Latitude (Geographic Coordinates Degrees)	Longitude (Geographic Coordinates Degrees)	Catchment	Total national potable water consumption (litres per person per day)	Country	Continent
Balderhead	54.5613	-2.1121		151 (Eurostat, 2015)	United Kingdom	
Thirlmere	54.5604	-3.0704	Ehen / Calder / Ellen			
Haweswater	54.5346	-2.7704	Eden			
Scar House	54.1888	-1.8996	Ouse			
Grimwith	54.0788	-1.9163				
Gouthwaite	54.1104	-1.7871				
Silent Valley	54.1288	-6.0038	Lagan			
Stocks	53.9871	-2.4313	Ribble			
Derwent	53.4079	-1.7446	Derwent			
Howden	53.4329	-1.7454				
Ladybower	53.3704	-1.7038				
Llyn Cowlyd	53.1521	-3.8913	Dovey			
Llyn Brenig	53.0788	-3.5413	Dee			
Alwen	53.0629	-3.5621				
Llyn Celyn	52.9488	-3.6746				
Vyrnwy	52.7663	-3.4579	Stour / Tern			
Clywedog	52.4746	-3.6038				
Craig-Goch	52.3079	-3.6238	Wye			
Claerwen	52.2621	-3.6621				
Caban Coch	52.2671	-3.5787				
Llyn Brianne	52.1246	-3.7663	Towy			
Talybont	51.8754	-3.3038	Usk			Europe

Reservoir Name	Latitude (Geographic Coordinates Degrees)	Longitude (Geographic Coordinates Degrees)	Catchment	Total national potable water consumption (litres per person per day)	Country	Continent
Colliford Water	50.5121	-4.5704	Tamar	151 (Eurostat, 2015)	United Kingdom	
Vartry Reservoir	53.0580	-6.2011	Liffey	123 (Expert Commission on Domestic Public Water Services, 2016)	Ireland	
Poulaphuca	53.1246	-6.5796				
Vesdre	50.6179	6.0913	Meuse	57 (Eurostat, 2015)	Belgium	
Lehnmuehle	50.8329	13.5921	Elbe	121 (Federal Statistical Office of Germany, 2013)	Germany	
Klingenberg	50.9063	13.5354				
Eibenstock	50.5313	12.5963	Mulde			
Přísečnice	50.4888	13.1338		123 (Eurostat, 2015)	Czech Republic	
Nýrsko	49.2604	13.1463	Vltava			
Vír	49.5663	16.3088	Morava			
Colby Lake	40.0882	-93.7656	St Louis	333 (Maupin et al., 2014)	United States	North America
O'Shaughnessy Reservoir	40.1579	-83.1279	Upper Scioto			
Hoover Reservoir (Ohio)	40.1121	-82.8788				
Jump Creek (Vancouver Island)	49.0104	-124.2204	South Central Vancouver Island	251 (Statistics Canada, 2013)	Canada	North America

Reservoir Name	Latitude (Geographic Coordinates Degrees)	Longitude (Geographic Coordinates Degrees)	Catchment	Total national potable water consumption (litres per person per day)	Country	Continent
Billings Reservoir	-23.7054	-46.6763	Tiete	167 (Sistema Nacional de Informações sobre Saneamento, 2016)	Brazil	South America
Guarapiranga	-23.6729	-46.7279				
Wanjiazhai	39.5829	111.4296	Lanyi He/Zhujia Chuan	147 (Ministry of Housing and Urban-Rural Development of of the People's Republic of China, 2011)	China	Asia
Corin Reservoir	-35.5354	148.8354	Murrumbidgee	290 (Water Corporation, 2010)	Australia	Oceania
Upper Mangatawhiri	-37.0838	175.1546	Waikato	460 (CH2M Beca Limited, 2010)	New Zealand	

Table D.1 (part II) Information of global PRI catchments.

Reservoir Name	Proportion of upstream flow accumulation that has interacted with peatlands	Mixed-source potable water supplied by reservoir (million litres per day)	Population using mixed-source peat-fed potable water (million persons)	PRI (million $m^3 yr^{-1}$)	Population using directly-sourced peat-fed potable water (million persons)	Remarks
Backwater	0.16	45.3 (The Gazetteer for Scotland, 2017)	0.30	2.69	0.0488	
Carron Valley	0.11	135 (Technical Inspection of Carron Valley WTW, 2015)	0.89	5.27	0.0963	
Loch Arklet	0.13	45.68 (Böhm and Merry, 2009)	0.30	2.11	0.0383	Provides water for Loch Katrine to supply gross 400 million litres per day via pipe
Glen Finglas	0.31	70.57 (Böhm and Merry, 2009)	0.47	8.10	0.1470	Provides water for Loch Katrine to supply gross 400 million litres per day via pipe
Loch Venacher	0.17	43.83 (Böhm and Merry, 2009)	0.29	2.78	0.0505	Provides water for Loch Katrine to supply gross 400 million litres per day via pipe

Reservoir Name	Proportion of upstream flow accumulation that has interacted with peatlands	Mixed-source potable water supplied by reservoir (million litres per day)	Population using mixed-source peat-fed potable water (million persons)	PRI (million m^3 yr^{-1})	Population using directly-sourced peat-fed potable water (million persons)	Remarks
Katrine	0.22	239.92 (Böhm and Merry, 2009)	1.59	19.46	0.3531	
Megget	0.59	102.3 (Edinburgh Council, 2006)	0.68	22.04	0.4026	
Talla	0.19	45 (Edinburgh Council, 2006)	0.30	3.05	0.0557	
Camps	0.09	28 (Scottish Water, 2017)	0.19	0.89	0.0162	
Daer	0.58	125 (Scottish Water, 2017)	0.83	26.38	0.4818	
Bradan	0.40	100 (Scottish Water, 2017)	0.66	14.71	0.2686	
Kielder Reservoir	0.63	344.38 (Environment Agency, 2017)	2.28	79.58	1.4535	
Derwent (Tees)	0.22	136 (Environment Agency, 2017)	0.90	11.13	0.2033	
Cow Green	0.85	38.6 (Environment Agency, 2017)	0.26	11.94	0.2180	
Selset	0.95	28.5 (Environment Agency, 2017)	0.19	9.86	0.1801	
Balderhead	0.79	145.48 (Environment Agency, 2017)	0.96	42.02	0.7675	

Reservoir Name	**Proportion of upstream flow accumulation that has interacted with peatlands**	**Mixed-source potable water supplied by reservoir (million litres per day)**	**Population using mixed-source peat-fed potable water (million persons)**	**PRI (million m^3 yr^{-1})**	**Population using directly-sourced peat-fed potable water (million persons)**	**Remarks**
Thirlmere	0.28	226.50 (Environment Agency, 2017)	1.50	23.19	0.4235	
Haweswater	0.40	121.38 (Environment Agency, 2017)	0.80	17.69	0.3231	
Scar House	0.67	104.56 (Environment Agency, 2017)	0.69	25.51	0.4660	
Grimwith	0.96	36.5 (Environment Agency, 2017)	0.24	12.76	0.2331	
Gouthwaite	0.38	37.9 (Environment Agency, 2017)	0.25	5.21	0.0952	
Silent Valley	0.55	130 (Environment Agency, 2017)	0.86	26.03	0.4754	
Stocks	0.26	104.62 (Environment Agency, 2017)	0.69	9.79	0.1789	
Derwent	0.87	150 (Environment Agency, 2017)	0.99	47.48	0.8671	
Howden	0.95	14.32 (Environment Agency, 2017)	0.09	4.94	0.0903	Provides water for Ladybower to supply gross 60 million litres per day

Reservoir Name	Proportion of upstream flow accumulation that has interacted with peatlands	Mixed-source potable water supplied by reservoir (million litres per day)	Population using mixed-source peat-fed potable water (million persons)	PRI (million m^3 yr^{-1})	Population using directly-sourced peat-fed potable water (million persons)	Remarks
Ladybower	0.59	45.68 (Environment Agency, 2017)	0.30	9.84	0.1798	Provides water for Ladybower to supply gross 60 million litres per day
Llyn Cowlyd	0.27	46 (Natural Resources Wales, 2017)	0.30	4.58	0.0836	
Llyn Brenig	0.31	9.1 (Natural Resources Wales, 2017)	0.06	1.02	0.0186	
Alwen	0.75	10.2 (Natural Resources Wales, 2017)	0.07	2.80	0.0512	
Llyn Celyn	0.67	47.75 (Natural Resources Wales, 2017)	0.32	11.72	0.2141	
Vyrnwy	0.49	210 (Natural Resources Wales, 2017)	1.39	37.77	0.6899	
Clywedog	0.11	55 (Natural Resources Wales, 2017)	0.36	2.17	0.0396	
Craig-Goch	0.86	35.61 (Natural Resources Wales, 2017)	0.24	11.20	0.2046	Provides water for Caban Coch to supply gross 360 million litres per day

Reservoir Name	Proportion of upstream flow accumulation that has interacted with peatlands	Mixed-source potable water supplied by reservoir (million litres per day)	Population using mixed-source peat-fed potable water (million persons)	PRI (million m^3 yr^{-1})	Population using directly-sourced peat-fed potable water (million persons)	Remarks
Claerwen	0.61	186.97 (Natural Resources Wales, 2017)	1.24	41.51	0.7582	Provides water for Caban Coch to supply gross 360 million litres per day
Caban Coch	0.42	137.42 (Natural Resources Wales, 2017)	0.91	20.95	0.3826	
Llyn Brianne	0.40	88.83 (Natural Resources Wales, 2017)	0.59	13.05	0.2384	
Talybont	0.08	40 (Natural Resources Wales, 2017)	0.26	1.23	0.0225	
Colliford Water	0.86	14.77 (Environment Agency, 2017)	0.10	4.64	0.0848	
Vartry Reservoir	0.42	77.5 (The Environmental Protection Agency, 2016)	0.52	11.86	0.2167	
Poulaphuca	0.35	275 (The Environmental Protection Agency, 2013)	1.83	34.63	0.6326	
Vesdre	0.05	45 (The Société wallonne des eaux, 2017;	0.40	0.83	0.0203	

Reservoir Name	**Proportion of upstream flow accumulation that has interacted with peatlands**	**Mixed-source potable water supplied by reservoir (million litres per day)**	**Population using mixed-source peat-fed potable water (million persons)**	**PRI (million m^3 yr^{-1})**	**Population using directly-sourced peat-fed potable water (million persons)**	**Remarks**
		Aubin and Varone, 2002; Bruwier et al., 2015)				
Lehnmuehle	0.50	49.40 (Slavik et al., 2010)	0.41	8.98	0.2049	Provides water for Klingenberg to supply gross 86.4 million litres per day
Klingenberg	0.34	36.00 (Eibenstock Anke Heiser and Ralf Sudbrack, 2007)	0.31	4.53	0.1034	
Eibenstock	0.55	74.4 (Eibenstock Anke Heiser and Ralf Sudbrack, 2007)	0.62	14.90	0.3403	
Přísečnice	0.16	43.08 (Kocí et al., 2016)	0.35	2.52	0.0560	
Nýrsko	0.17	22.14 (Mikulecký and Ponce, 2017)	0.18	1.34	0.0298	
Vír	0.24	99.36 (Brněnské vodárny a	0.81	8.58	0.1911	

Reservoir Name	Proportion of upstream flow accumulation that has interacted with peatlands	Mixed-source potable water supplied by reservoir (million litres per day)	Population using mixed-source peat-fed potable water (million persons)	PRI (million m^3 yr^{-1})	Population using directly-sourced peat-fed potable water (million persons)	Remarks
		kanalizace, 2017)				
Colby Lake	0.80	5.68 (Minnesota Department of Health, 2002)	0.02	1.66	0.0123	
O'Shaughnessy Reservoir	0.56	110 (Leslie et al., 2014)	0.30	22.54	0.1669	
Hoover Reservoir (Ohio)	0.01	380 (Leslie et al., 2014)	1.03	1.51	0.0112	
Jump Creek (Vancouver Island)	0.23	225 (City of Nanaimo, 2007)	0.68	18.48	0.1535	
Billings Reservoir	0.13	375 (García, 2010)	2.25	18.42	0.3022	
Guarapiranga	0.02	684 (Oliver et al., 2016)	4.10	5.08	0.0833	
Wanjiazhai	0.00	3835.6 (China Internet Information Center, 2017)	25.57	2.04	0.0373	
Corin Reservoir	0.00	137.55 (Icon Water Limited, 2017)	0.49	0.04	0.0004	
Upper Mangatawhiri	0.01	54 (Engineering New Zealand, 2017	0.32	0.17	0.0027	

Table D.2 Condensed land use of water-supply peatlands.

General land use	Specify land use
Pristine or protected	Forest - protected
	Grasslands - unmanaged
	Grasslands - protected
	Shrubs - unmanaged
	Shrubs - protected
	Agriculture - protected
	Sparsely vegetated areas - protected
	Open Water - unmanaged
	Open Water - protected
Low agricultural activities	Shrubs - low livestock density
Moderate or higher agricultural activities	Forest - with agricultural activities
	Forest - with moderate or higher livestock density
	Grasslands - moderate livestock density
	Grasslands - high livestock density
	Shrubs - moderate livestock density
	Shrubs - high livestock density
	Rain-fed crops (Subsistence/Commercial)
	Crops and moderate intensive livestock density
	Crops and high livestock density
	Open Water - inland Fisheries
Settlement	Settlement land

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Appendix E
Supplementary notes for Chapter 3 (Paper II)

E.1 Introduction to potable water supply by peatlands in the PPI hotspots

This appendix focuses on the eight catchments identified from the global analysis as PPI hotspots for more detailed study of their water resource networks in order to test the reliability of the coarser, global-scale PPI as an indicator of the importance of peatlands to potable water resource provision. In doing so this study considers information on water supply and redistribution systems in each catchment and their hydrological connection to peatlands, the proportion of flow accumulation that has interacted with peatlands before draining into streams from which drinking water is abstracted, and the population that use potable water from these peat-influenced sources. This study do not consider the Peat Reservoir Index (PRI) here, which is dealt with separately in Methods in Chapter 3.

E.2 River Liffey catchment, Republic of Ireland

The River Liffey catchment, in the east of the Republic of Ireland, encompasses all of Dublin city and county, as well as parts of Counties Wicklow and Kildare, and includes extensive peatland cover in the Wicklow Mountains. The Ballymore Eustace is the largest water treatment plant in the Dublin region network, supplying water to the Great Dublin Region, and is fed by Poulaphuca Lake on the Upper Liffey (marked by the black ellipse in Figure E.1). Water is abstracted from Poulaphuca Lake and treated in Ballymore Eustace Water Treatment Plant. Treated water is then redistributed to Dublin. The plant normally produces approximately 275,000 m^3 per day (The Environmental Protection Agency, 2013).

The Leixlip Plant (in the black triangle of Figure E.1), treating water from the Middle River Liffey is the second largest water treatment plant in the Dublin region and supplies approximately 30 % of the Dublin Region's drinking water requirements (approximately 160,000 m^3 per day), supplying North Dublin City and County as well as parts of South County Dublin and Kildare (The Environmental Protection Agency, 2012).

The Vartry Reservoir is in east Wicklow (in the black rectangle of Figure E.1). The Vartry Water Supply Scheme provides drinking water for a supply area stretching from Roundwood, through North Wicklow up to South Dublin. The Vartry Water Supply Scheme produces approximately 77,500 m^3 per day.

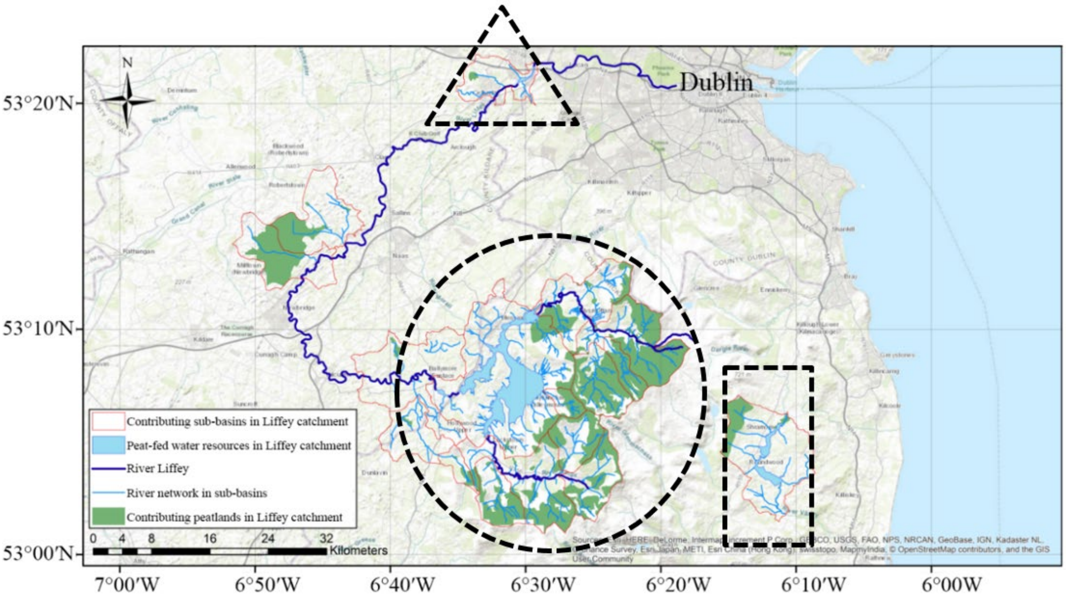

Figure E.1 River system and contributing peatlands for sources of domestic water in River Liffey catchment.

Table E.1 shows that peatlands in the Liffey catchment directly deliver approximately 56.20 million m^3 yr^{-1} of potable water (directly-sourced peat-fed water), equivalent to supporting a population of 1.25 million people on a per-capita basis.

Table E.1 Potable water supply by peatlands in Liffey catchment (The Environmental Protection Agency, 2016).

Water source	Potable water supplied from peat-fed water sources (mixed-source peat-fed water, million m^3 yr^{-1})	Percentage of flow accumulation that has interacted with peatlands upstream of water abstraction	Potable water directly from peatlands (directly-sourced peat-fed water, million m^3 yr^{-1})	Per capita usage of directly-sourced peat-fed water (million persons)
Poulaphuca Lake	100.38	34.50%	34.63	0.77
Leixlip Plant	58.40	16.63%	9.71	0.22
Vartry Reservoir	28.29	41.94%	11.86	0.26
Total	**187.07**	/	**56.20**	**1.25**

E.3 River Ribble catchment, England

The Ribble catchment in north-west England consists of the Ribble, Douglas and Wyre sub-basins, and is home to more than 2 million people.

The River Ribble and its major tributaries rise in the rural hills of the Yorkshire Dales (Ribblehead), then flows through the urban centre of Preston and discharges into Morecambe Bay via the Ribble Estuary. The mid Ribble is joined south of Clitheroe by two major tributaries: the Hodder and the Calder. The Calder catchment includes the main River Calder which originates from the moorlands surrounding Nelson, Burnley, Colne and Accrington, before joining the Ribble below Whalley. Historically this area was heavily industrialized (mill workings, paper production and so on) and much of the Calder and its tributaries were altered and impacted by industrial and urban development. The catchment is predominantly urban.

The River Hodder rises in the Forest of Bowland where it is dammed near to its source to form Stocks Reservoir, which provides a large proportion of drinking water for Blackburn and its suburbs.

The River Douglas rises in the South Pennines before flowing out onto low gradient, fertile agricultural land and then joining the River Ribble just above the latter’s estuarine mouth. The River Wyre rises in the Forest of Bowland in central Lancashire and flows into the Irish Sea at Fleetwood.

Figure E.2 shows the distribution of the river system and contributing peatlands for sources of potable water in the River Ribble catchment. Table E.2 shows peatlands in the River Ribble catchment annual directly deliver about 19.01 million m^3 yr^{-1} of river-supplied potable water (directly-sourced peat-fed water). In addition, peatlands in the Ribble catchment directly deliver 9.79 million m^3 yr^{-1} of reservoir-supplied potable water. Peatlands in the Ribble catchment directly deliver 28.80 million m^3 yr^{-1} of potable water (directly-sourced peat-fed water), equivalent to supporting a population of 0.52 million people on a per capita basis.

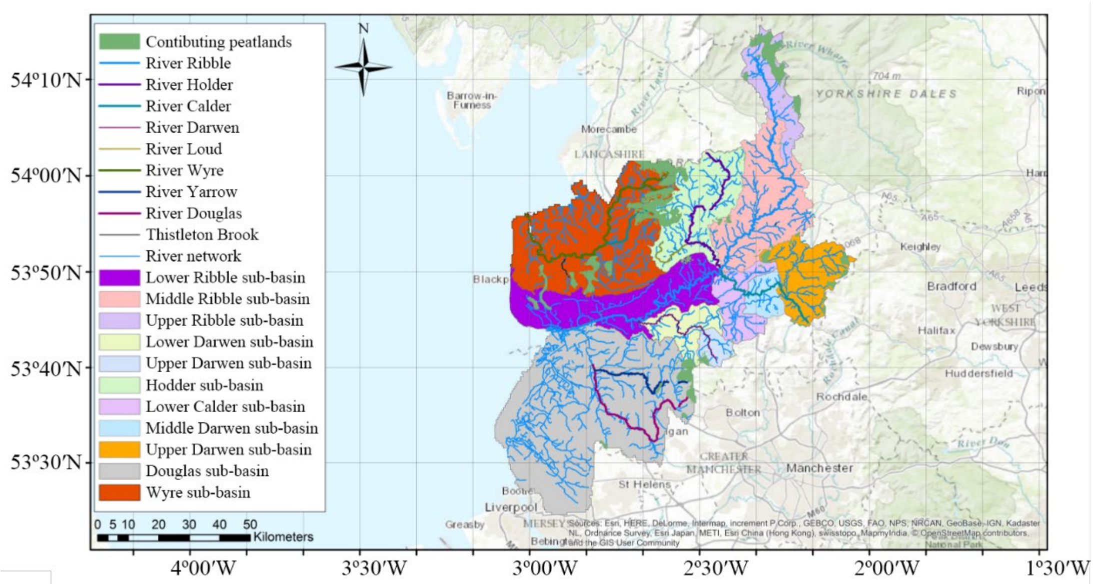

Figure E.2 River system and contributing peatlands for sources of domestic water in Ribble catchment.

Table E.2 Potable water supply by peatlands in Ribble catchment (Environment Agency, 2013a).

Water source	**Potable water supplied from peat-fed water sources (mixed-source peat-fed water, million m^3 yr^{-1})**	**Percentage of flow accumulation that has interacted with peatlands upstream of water abstraction**	**Potable water directly from peatlands (directly-sourced peat-fed water, million m^3 yr^{-1})**	**Per capita usage of directly-sourced peat-fed water (million persons)**
		Ribble Sub-Catchment Area		
Upper Darwen	4.56	12.38 %	0.56	0.010
Lower Darwen	42.92	6.24 %	2.68	0.049
River Loud	8.32	9.69 %	0.81	0.015
Upper Calder	37.49	12.54 %	4.7	0.085
Middle Calder	19.27	10.19 %	1.96	0.036
Lower Calder	43.4	8.08 %	3.51	0.064

Water source	**Potable water supplied from peat-fed water sources (mixed-source peat-fed water, million m^3 yr^{-1})**	**Percentage of flow accumulation that has interacted with peatlands upstream of water abstraction**	**Potable water directly from peatlands (directly-sourced peat-fed water, million m^3 yr^{-1})**	**Per capita usage of directly-sourced peat-fed water (million persons)**
Upper Ribble	1.35	43.80 %	0.59	0.011
Middle Ribble	8.03	11.93 %	0.96	0.017
Lower Ribble	21.35	7.44 %	1.59	0.029
Stocks Reservoir	38.19	25.65 %	9.79	0.178
Douglas Sub-Catchment Area				
River Yarrow	14.82	5.44 %	0.81	0.015
River Douglas	10.91	7.23 %	0.79	0.014
Wyre Sub-Catchment Area				
Thistleton Brook	0.11	44.05 %	0.048	0.001
Total	**250.72**	**/**	**28.80**	**0.52**

E.4 River Aire and Calder catchment, England

The Aire and Calder catchment encompasses an area of northern England stretching from Malham and Todmorden in the west to the River Ouse in the east. The River Calder rises on the Pennine Moors west of Todmorden and joins the River Aire at Castleford. The River Aire rises high in the Pennine Hills, near Malham in the Yorkshire Dales National Park. It flows south-east through limestone moorland areas, through Keighley, Bingley, Bradford and Leeds.

The estimates of water supplied from the Aire Headwaters, Upper Aire, Worth and Colne Rivers were derived from the Environment Agency water abstraction licensing strategy. However, the Environment Agency has no jurisdiction over abstraction from the River Calder, which is not included in the Abstraction Licensing Strategy. Due to legislation and commercial sensitivity, it was not possible to obtain details of the water supply grid for the drinking water supply system of River Calder. However, Yorkshire Water confirmed via e-mail that the River Calder provides approximately 130 million litres per day (ML d^{-1}) for the Calderdale area, in addition to 24 ML d^{-1} that is transferred for consumption outside of the Calderdale area (e.g., Wakefield). Therefore, this study assumed that River Calder provides 154 ML d^{-1} of potable water for human use.

Figure E.3 shows the locations of peatlands relative to river channels in the Aire and Calder catchment. Peatlands in the Aire and Calder catchment deliver 9.25 million m^3 yr^{-1} of directly-sourced peat-fed water, equivalent to supporting a population of 0.168 million people on a per capita basis (Table E.3).

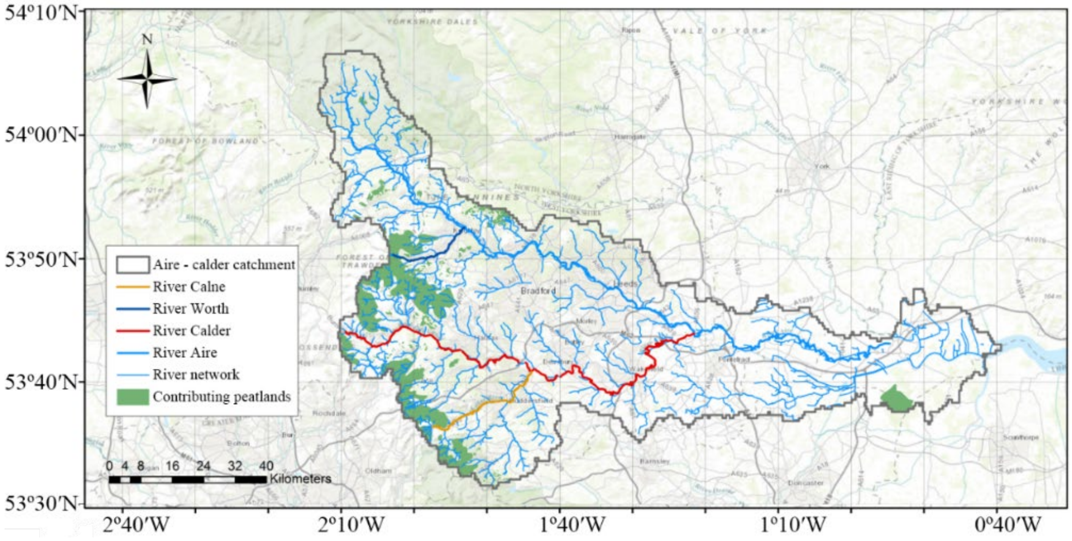

Figure E.3 River system and peatlands in Aire and Calder catchment.

Table E.3 Potable water supply by peatlands in river Aire and Calder catchment (Environment Agency, 2013b).

Water source	Potable water supplied from peat-fed water sources (mixed-source peat-fed water, million m^3 yr^{-1})	Percentage of flow accumulation that has interacted with peatlands upstream of water abstraction	Potable water directly from peatlands (directly-sourced peat-fed water, million m^3 yr^{-1})	Per capita usage of directly-sourced peat-fed water (million persons)
Aire Headwaters	0.29	7.99 %	0.03	0.0005
Upper Aire	1.83	10.21 %	0.19	0.003
River Worth	1.75	31.15 %	0.55	0.010
River Colne	2.45	14.84 %	0.36	0.007
River Calder	56.21*	14.45 %	8.12	0.147
Total	**62.53**	**/**	**9.25**	**0.1675**

* From Yorkshire Water company internal data.

E.5 PPI hotspots in the Netherlands

Table E.4 shows rates and sources of drinking water abstraction in 2014 for all water companies in The Netherlands. The water-supply networks operated by PWN, Waternat, Dunea and Oaseo contain water-supply peatlands, and delivered a combined total of 127 million m^3 of surface water and 43 million m^3 of ground water in 2014. Dunea abstracts surface water from the River Nieuwe Maas; PWN abstracts surface water from the huge offshore freshwater reservoir - the Ijsselmeer, and from the River Lek (more than 65% of water purified and distributed by PWN is taken from the IJsselmeer at the Andijk intake station); while Waternat, which is responsible for all water supply to the Amsterdam region, also abstracts surface water from the IJsselmeer. The IJsselmeer is fed primarily by the River IJssel, a distributary of the River Rhine (Figure E.4), which have virtually no surface hydrological connection to peatlands. Only the River Nieuwe Maas and River Lek have surface hydrological connections to peatlands. Peatlands in the Oude Rijn and Zuiderzee catchments have no interaction with local drinking water resources.

Table E.4 Annual potable water abstraction for 2014 for all water companies in Netherlands (million m^3) (Vewin, 2015).

Water company	Total	Ground water	River groundwater	Natural dune water	Surface water
Brabant Water	181	181	/	/	/
Dunea	77	/	/	/	77
Evides Waterbedrijf	204	17	/	/	187
Oasen	43	6	37	/	/
PWN	32	5	/	2	25
Vitens	352	342	10	/	/
Waternat	36	/	/	12	25
Waterbedrijf Groningen	47	42	/	/	5
Waterleidingmaatschappij Drenthe	32	32	/	/	/
WML	72	54	21	/	/
Watertransportmattschappij Rijn-Kennemerland	148	/	/	/	148
Total	**1224**	**675**	**68**	**14**	**466**

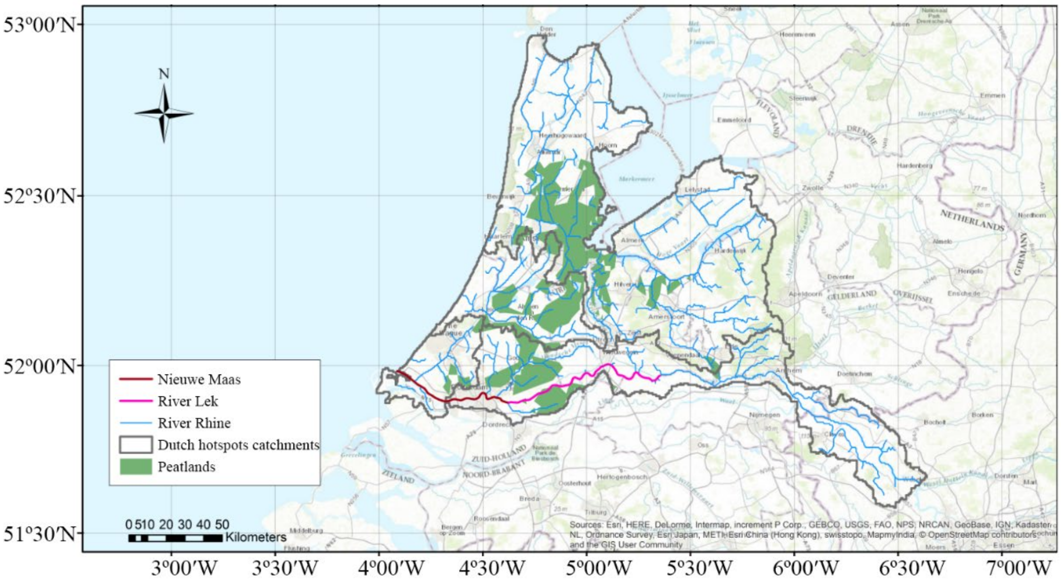

Figure E.4 River system and peatlands in four Dutch high PPI sub-basins.

Very few streams interact with peatlands upstream of water sources in the Dutch PPI hotspots (Table E.5). Peatlands in these catchments provide only 0.348 million m^3 yr^{-1} of potable water to abstracted rivers (directly-sourced peat-fed water), equivalent to supporting a population of approximately 8,000 people on a per-capita basis. Despite being identified as PPI hotspots, the detailed analysis of peatlands in the Netherlands reveals that these lowland ecosystems are of little consequence to water security there insofar as they have little connection to potable water supply networks.

Table E.5 Drinking water supply by peatlands in Nieuwe Maas and River Lek.

Water source	**Potable water supplied from peat-fed water sources (mixed-source peat-fed water, million m^3 yr^{-1})**	**Percentage of flow accumulation that has interacted with peatlands upstream of water abstraction**	**Potable water directly from peatlands (directly-sourced peat-fed water, million m^3 yr^{-1})**	**Per capita usage of directly-sourced peat-fed water (million persons)**
Nieuwe Maas	77.02	0.45 %	0.347	7978
River Lek	8.76	0.01 %	0.001	20
Total	**85.78**	**/**	**0.348**	**7998**

E.6 Everglades catchment, Florida

The Everglades catchment encompasses 10,359 km^2 in the south of the state of Florida, extending from the southern shore of Lake Okeechobee to the mangrove estuaries of Florida Bay. The Everglades occupy a limestone basin that has accumulated layers of peat and mud, bathed by freshwater from Lake Okeechobee. Much of the central and southern parts of the catchment are covered by wetlands, including large expanses of peatlands. Peatlands adjoining the southern shore of Lake Okeechobee have been heavily modified for agricultural use, although more intact systems remain further south, including in the Everglades National park and several other protected areas.

Table E.6 Total water abstraction by county and source (million m^3) in Everglades catchment, 2015 (South Florida Water Management District, 2015).

County	Fresh Water	Saline Water	Surface Water	Groundwater	Total Use
Broward	305.74	17.11	0.00	322.83	322.83
Hendry	0.80	3.77	0.00	4.57	4.57
Martin	10.00	11.55	0.00	21.57	21.57
Miami-Dade	467.55	18.02	0.00	486.24	486.25
Palm Beach	306.04	37.62	40.40	289.45	329.85
St. Lucie	11.32	29.25	0.00	40.58	40.58
Total	**1101.44**	**117.32**	**40.40**	**1165.24**	**1205.65**

Drinking water abstraction in the Everglades catchment is dominated by groundwater sources, which provided approximately 1.17 billion m^3 in 2015, compared to just approximately 40.4 million m^3 from surface water sources (Table E.6). All of this 40.4 million m^3 of surface water was derived from Clear Lake (Latitude 26.7120, Longitude -80.0696) and used by the County of Palm Beach. The Clear Lake is indirectly connected to Lake Okeechobee via a series of tie-back canals, which flow through the Everglades Agricultural Area (South Florida Water Management District, 2013). The peatlands in the Everglades Agricultural Area have been drained for agricultural development since the 1800s and there is virtually no surface hydrological connection to the series of tie-back canals now (Hohner and Dreschel, 2015). Lake Okeechobee receives water directly from rainfall and from its major tributaries the Kissimmee River, Fisheating Creek, and Taylor Reek/Nubbin Slough, none of which have important upstream interactions with peatlands. A number of surface canals drain south from Lake Okeechobee, providing irrigation for agricultural activities in the relict peatlands on its southern shore, before flowing south-east through Miami to the Atlantic without being utilised for drinking water. Much like the high-PPI Dutch catchments (above), despite containing both high percentage cover of peatlands and a large population centre, peatlands in the Everglades catchment are of little consequence to the security of drinking water resources there, largely due to their lowland topographic location.

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Appendix F
Supplementary tables for Chapter 4 (Paper III)

Table F.1 Characteristics of all nine peatland-derived drinking water supply catchments in the UK between 2005 and 2016.

Catchment outlet	Latitude (Degrees)	Longitude (Degrees)	Catchment area (km^2)	Catchment land cover	Mean/ standard deviations of temperature (°C)	Mean/ standard deviations of daily precipitation (mm)	Mean/ standard deviations of discharge (m^3 s^{-1})	Mean/ standard deviations of DOC concentration (mg L^{-1})	Annual potable water directly supplied by peatlands (million m^3)
Tyne at Bywell	54.949937	-1.9422021	2,176	Grassland (62%), agriculture (4%), peatland (12%) and forest (22%)	9.4/5.07	2.01/ 4.17	50.87/ 57.35	9.73/ 3.71	90.71
Wye at Redbrook	51.795638	-2.6872644	4,010	Grassland (62%), agriculture (17%), peatland (5%), forest (14%) and urban (2%)	10.2/ 5.34	2.85/ 6.22	73.34/ 79.89	3.17/ 1.52	73.66
Tees at Broken Scar	54.51794	-1.6014185	818	Grassland (59%), agriculture (13%), peatland (24%) and forest (4%)	9.7/ 5.06	1.92/ 4.21	21.99/ 29.00	8.45/ 3.93	63.82

Derwent at Wilne Church (Derbyshire)	52.880064	-1.3461477	1,177.5	Grassland (60%), agriculture (12%), peatland (9%), forest (10%) and urban (9%)	10.8/ 5.41	1.74/ 3.58	18.75/19.10	3.83/ 0.92	62.26
Ouse at Skelton	53.990631	-1.1351792	3,315	Grassland (44%), agriculture (32%), peatland (13%), forest (7%) and urban (4%)	10.3/ 5.42	1.90/ 3.96	54.92/ 65.00	6.32/ 3.19	43.49
Severn at Montford	52.724025	-2.8735293	2,025	Grassland (70%), agriculture (6.5%), peatland (5%), forest (17%) and urban (1.5%)	10.2/ 5.25	1.81/ 3.79	45.76/ 53.30	4.49/ 1.78	39.94
Ribble at Samlesbury	54.603794	-3.1609979	1,145	Grassland (71%), agriculture (3%), peatland (9%), forest (10%) and urban (7%)	10.1/ 5.08	3.02/ 5.12	36.14/ 50.32	6.04/ 2.30	28.79
Derwent at Portinscale (Cumbria)	54.603794	-3.1609979	235	Grassland (73%), agriculture (2%), peatland (13%), forest (11%) and urban (1%)	9.1/ 5.01	2.79/ 4.72	13.75/ 14.21	1.76/ 0.61	23.19
Eamont at Udford	54.666874	-2.6604446	396	Grassland (78%), agriculture (4%), peatland (7%), forest (9%) and urban (2%)	9.4/ 5.05	2.34/ 4.21	18.53/ 24.07	2.47/ 0.80	17.69

Table F.2 Statistically significant sensitive parameters for discharge modelling according to the Kolmogorov-Smirnov (KS) test

Catchment	ParName	Parameter description	D	p
Tyne	*RainMultiplier*	Adjustment factor relating measured precipitation to estimated rainfall	0.64	<0.05
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.50	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box.	0.44	
	DegreeDayEvapotranspiration	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.44	
Tees	*DegreeDayEvapotranspiration*	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.60	
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.32	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box.	0.25	
Ouse	*b*	Parameter b to determine flow velocity as $v = a*Q^b$	0.69	
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.43	

Catchment	ParName	Parameter description	D	p
Dewent (Derbyshire)	*GrowingDegreeThreshold*	Temperature threshold above which evapotranspiration can occur (°C)	0.29	<0.05
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box.	0.23	
	SnowMultiplier	Adjustment factor relating measured precipitation to estimated snowfall	0.22	
	SnowMultiplier	Adjustment factor relating measured precipitation to estimated snowfall	0.40	
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.33	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box.	0.32	
	DegreeDayEvapotranspiration	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.32	
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.26	
Severn	b	Parameter b to determine flow velocity as $v = a*Q^b$	0.88	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box.	0.33	
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.26	

Catchment	ParName	Parameter description	D	p
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.22	<0.05
Wye	*SnowMelt*	Adjustment factor relating measured precipitation to estimated snowfall	0.67	
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.65	
	b	Parameter b to determine flow velocity as $v = a*Q^b$	0.62	
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.46	
	DegreeDayEvapotranspiration	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.34	
Ribble	*ResidenceTime*	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box	0.66	
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.52	
	SnowMultiplier	Adjustment factor relating measured precipitation to estimated snowfall	0.45	
	DegreeDayEvapotranspiration	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.32	
Derwent (Cumbria)	*b*	Parameter b to determine flow velocity as $v = a*Q^b$	0.50	

Catchment	ParName	Parameter description	D	p
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.36	<0.05
	GrowingDegreeThreshold	Temperature threshold above which evapotranspiration can occur (°C)	0.31	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box	0.26	
Eamont	*GrowingDegreeThreshold*	Temperature threshold above which evapotranspiration can occur (°C)	0.55	
	RainMultiplier	Adjustment factor relating measured precipitation to estimated rainfall	0.54	
	DegreeDayEvapotranspiration	Depth of water lost due to evapotranspiration per degree per day when temperature exceeds the limit at which evapotranspiration occurs	0.54	
	ResidenceTime	It represents the residence time of water in a soil box as a proxy to the hydrological connectivity of that particular soil box	0.36	
	b	Parameter *b* to determine flow velocity as $v = a*Q^b$	0.24	

Table F.3 Statistically significant sensitive parameters for DOC modelling according to the Kolmogorov-Smirnov (KS) test

Catchment	ParName	Parameter description	D	p
Tyne	*flow_b*	Parameter *b* to determine flow velocity as $v = a*Q^b$	0.37	<0.05
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution (i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.26	
	MineralLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the mineral layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.23	
	BaseFlowIndex	Fraction of water that goes to the lower layer from the upper layer.	0.21	
Tees	*flow_b*	Parameter *b* to determine flow velocity as $v = a*Q^b$	0.24	
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.22	
Ouse	*flow_b*	Parameter b to determine flow velocity as $v = a*Q^b$	0.32	
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.30	
	MineralLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the mineral layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.23	
Derwent (Derbyshire)	*ZeroRateDepth*	It is used to regulate transformation rates at different moisture conditions. Above a specified SMD (‘Zero rate depth’), processes are turned off, and below they linearly increase until the base level at another specified SMD value (‘Max rate depth’).	0.41	

Catchment	ParName	Parameter description	D	p
	DOCToDICRadiationMultiplier	It represents a factor controlling the amount of DOC that can be mineralized to DIC as a consequence of photodegradation in the aquatic system.	0.35	<0.05
	MineralLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the mineral layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.30	
Severn	*flow_b*	Parameter b to determine flow velocity as $v = a*Q^b$	0.38	
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.29	
Wye	*flow_b*	Parameter b to determine flow velocity as $v = a*Q^b$	0.47	
	OpenWaterDOCToDICMicrobial	Velocity in which DOC is transformed into DIC in the stream as a consequence of microbial degradation (/day). It represents the amount of DOC that can be transformed into DIC in a day by the microbial community in the stream (/day)	0.37	
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.24	
Ribble	*DOCToDICRadiationMultiplier*	It represents a factor controlling the amount of DOC that can be mineralized to DIC as a consequence of photodegradation in the aquatic system.	0.44	
	RainfallExcessProportion	Fraction of the calculated amount of recharge water that do not infiltrate the soil but stays over the surface at every time step.Higher number would mean much more runoff will be generated from overland flow, which would usually imply faster flow responses and lower DOC mobilization (and vice versa).	0.36	
	OrganicLayerFastPoolFraction	Fraction of the total SOC in the upper layer that belongs to the fast pool. The lower layer is divided into a fast SOC pool where carbon produced and easily leachable and a slow carbon pool where carbon is not available at the time step.	0.31	

Catchment	ParName	Parameter description	D	p
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.21	<0.05
Derwent (Cumbria)	*flow_b*	Parameter *b* to determine flow velocity as $v = a*Q^b$	0.38	
	OrganicLayerB2	Parameter *b2* to determine the decrease in carbon solubility in the organic layer when there is a strong acidifying anion (i.e. sulphate) present in the soils solution, i.e. limiting the SOC desorption into DOC, such as $dDOC/dt = -(k2 + b1 \cdot [anion]exp\ b2) \cdot DOC + k1 \cdot SOC$	0.30	
	COUP_10DegreeResponse	Process-rate response to a 10 °C soil temperature change	0.28	
	MineralLayerFastPoolFraction	Fraction of the total SOC in the lower layer that belongs to the fast pool. The lower layer is divided into a fast SOC pool where carbon produced and easily leachable and a slow carbon pool where carbon is not available at the time step	0.27	
Eamont	*flow_b*	Parameter *b* to determine flow velocity as $v = a*Q^b$	0.42	
	OpenWaterDOCToDICMicrobial	Velocity in which DOC is transformed into DIC in the stream as a consequence of microbial degradation (/day). It represents the amount of DOC that can be transformed into DIC in a day by the microbial community in the stream (/day)	0.39	
	MineralLayerFastPoolFraction	Fraction of the total SOC in the lower layer that belongs to the fast pool. The lower layer is divided into a fast SOC pool where carbon produced and easily leachable and a slow carbon pool where carbon is not available at the time step	0.22	
	COUP_10DegreeResponse	Process-rate response to a 10 °C soil temperature change.	0.22	

Table F.4 Values of monthly averaged observed flow, DOC concentration, and DOC flux at all nine catchments in baseline and the potential projected values from the low GHG emission (B1), medium GHG emission (A1B) and high GHG emission (A1F1) scenarios for the 2030s and the 2090s.

Catchment	Items	Month	Baseline	2030s	2030s	2030s	2090s	2090s	2090s
				B1	A1B	A1F1	B1	A1B	A1F1
Tyne catchment	Discharge (m^3 s^{-1})	JAN	60.65	58.20	60.51	60.35	62.34	61.55	61.25
		FEB	53.13	53.10	53.93	53.90	54.90	55.02	53.59
		MAR	44.65	47.91	40.98	40.86	37.93	37.43	34.56
		APR	40.15	41.26	33.18	33.28	30.50	29.25	25.37
		MAY	39.92	37.31	27.37	27.83	23.63	20.96	16.61
		JUN	32.44	27.51	17.27	17.07	14.03	11.50	9.27
		JUL	38.47	31.79	18.64	18.67	14.72	11.61	9.28
		AUG	39.71	23.72	13.27	13.48	10.53	9.03	8.10
		SEP	47.57	33.33	23.61	23.15	17.02	13.78	12.40
		OCT	40.18	27.57	19.16	18.91	15.72	13.92	13.56
		NOV	60.80	56.30	42.15	40.71	36.12	30.47	32.83
		DEC	60.71	63.77	57.94	57.03	57.29	53.95	57.51
		Mean	46.53	41.81	34.00	33.77	31.23	29.04	27.86
	DOC concentration (mg L^{-1})	JAN	8.46	11.03	14.18	14.35	17.21	19.05	19.25
		FEB	7.69	9.47	11.32	11.42	12.99	13.91	14.25
		MAR	7.24	9.07	9.62	9.67	10.49	10.87	10.67
		APR	7.28	8.46	8.65	8.68	9.06	9.21	8.88
		MAY	7.85	8.43	8.40	8.48	8.48	8.37	7.86
		JUN	8.09	8.36	8.20	8.13	8.21	7.90	7.57
		JUL	9.64	9.92	10.48	10.45	10.43	10.19	10.01
		AUG	11.85	10.71	10.77	10.83	10.49	10.42	10.92
		SEP	11.35	10.74	11.29	11.22	11.78	11.88	12.27
		OCT	12.53	12.49	12.74	12.73	13.17	13.53	14.10
		NOV	11.92	16.16	18.58	18.48	20.36	20.22	21.16
		DEC	9.97	14.18	18.90	19.08	23.31	25.14	25.94

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
		Mean	9.49	10.75	11.93	11.96	13.00	13.39	13.57
Tyne catchment	**DOC flux (g of OC m^{-2} month^{-1})**	**JAN**	0.61	0.76	1.02	1.03	1.28	1.40	1.40
		FEB	0.49	0.60	0.73	0.73	0.85	0.91	0.91
		MAR	0.39	0.52	0.47	0.47	0.47	0.48	0.44
		APR	0.35	0.42	0.34	0.34	0.33	0.32	0.27
		MAY	0.37	0.37	0.27	0.28	0.24	0.21	0.16
		JUN	0.31	0.27	0.17	0.17	0.14	0.11	0.08
		JUL	0.44	0.38	0.23	0.23	0.18	0.14	0.11
		AUG	0.56	0.30	0.17	0.17	0.13	0.11	0.11
		SEP	0.64	0.43	0.32	0.31	0.24	0.19	0.18
		OCT	0.60	0.41	0.29	0.29	0.25	0.22	0.23
		NOV	0.86	1.08	0.93	0.90	0.88	0.73	0.83
		DEC	0.72	1.08	1.30	1.30	1.59	1.62	1.78
		Total	6.35	6.62	6.25	6.22	6.57	6.45	6.49
Tees catchment	**Discharge (m^3 s^{-1})**	**JAN**	31.12	32.74	33.35	33.24	34.73	34.39	34.76
		FEB	22.43	24.32	24.48	24.55	24.47	24.67	24.73
		MAR	21.76	20.18	19.76	19.64	18.53	18.29	17.99
		APR	20.79	17.28	17.03	17.18	15.92	15.25	14.24
		MAY	17.00	13.99	13.68	13.92	12.02	10.59	9.35
		JUN	12.71	9.20	9.04	8.90	7.75	6.67	5.93
		JUL	16.40	11.60	11.36	11.54	9.54	8.05	6.80
		AUG	13.76	8.42	8.29	8.42	6.88	6.01	5.47
		SEP	17.97	12.43	12.66	12.39	8.84	7.49	6.55
		OCT	18.29	11.65	11.59	11.38	9.69	8.82	7.82
		NOV	34.74	30.03	30.17	29.38	27.65	24.56	21.93
		DEC	31.30	31.60	31.61	31.28	31.63	30.83	31.49
		Mean	21.52	18.62	18.58	18.49	17.30	16.30	15.59

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Tees catchment	DOC concentration (mg L^{-1})	JAN	5.25	6.92	6.91	6.97	7.87	8.51	9.05
		FEB	5.52	6.59	6.57	6.59	7.11	7.36	7.63
		MAR	6.02	6.83	6.83	6.84	7.23	7.27	7.43
		APR	6.19	7.00	7.04	7.06	7.50	7.64	7.84
		MAY	6.86	7.93	7.94	7.97	8.51	8.52	8.66
		JUN	7.95	9.04	9.01	9.03	9.57	9.51	9.53
		JUL	9.29	11.31	11.37	11.37	12.21	12.40	12.49
		AUG	10.50	12.63	12.58	12.63	13.46	13.41	13.64
		SEP	9.75	11.46	11.50	11.45	12.52	12.99	13.29
		OCT	10.59	12.87	12.82	12.79	14.09	14.44	14.93
		NOV	9.19	13.59	13.62	13.70	15.91	16.44	17.09
		DEC	6.16	9.07	9.07	9.22	11.16	12.40	13.74
		Mean	7.77	9.60	9.61	9.63	10.60	10.91	11.28
	DOC flux (g of OC m^{-2} $month^{-1}$)	JAN	0.52	0.72	0.73	0.73	0.87	0.93	1.00
		FEB	0.39	0.51	0.51	0.51	0.55	0.57	0.60
		MAR	0.41	0.44	0.43	0.43	0.42	0.42	0.42
		APR	0.41	0.38	0.38	0.38	0.38	0.37	0.35
		MAY	0.37	0.35	0.34	0.35	0.32	0.29	0.26
		JUN	0.32	0.26	0.26	0.25	0.23	0.20	0.18
		JUL	0.48	0.42	0.41	0.42	0.37	0.32	0.27
		AUG	0.46	0.34	0.33	0.34	0.29	0.26	0.24
		SEP	0.55	0.45	0.46	0.45	0.35	0.31	0.28
		OCT	0.61	0.47	0.47	0.46	0.43	0.40	0.37
		NOV	1.01	1.29	1.30	1.27	1.39	1.28	1.19
		DEC	0.61	0.91	0.91	0.91	1.12	1.21	1.37
		Total	6.15	6.54	6.53	6.51	6.74	6.55	6.51
Ouse catchment	Discharge (m^3 s^{-1})	JAN	96.00	93.47	94.88	93.43	94.02	89.62	89.77

Catchment	**Items**	**Month**	**Baseline**	**2030s B1**	**2030s A1B**	**2030s A1F1**	**2090s B1**	**2090s A1B**	**2090s A1F1**
Ouse catchment	**Discharge (m^3 s^{-1})**	**FEB**	76.57	77.39	77.99	77.99	78.62	78.49	78.32
		MAR	76.44	71.50	70.42	70.19	68.30	68.01	66.12
		APR	62.97	56.51	55.39	55.51	51.86	49.92	46.55
		MAY	56.57	44.01	43.15	43.74	38.75	35.27	32.27
		JUN	43.57	32.27	31.76	31.25	28.28	24.67	22.51
		JUL	41.75	32.34	31.86	31.52	28.22	24.61	21.76
		AUG	33.13	24.82	24.36	24.76	21.15	18.36	16.00
		SEP	32.09	24.03	24.19	24.13	20.29	17.98	15.94
		OCT	35.76	26.56	26.71	26.30	21.74	19.67	17.41
		NOV	65.74	48.46	48.42	46.88	41.16	35.16	30.75
		DEC	87.49	83.64	83.79	82.29	81.18	75.24	74.33
		Mean	59.01	51.25	51.08	50.67	47.80	44.75	42.64
	DOC concentration (mg L^{-1})	**JAN**	4.73	5.58	5.59	5.63	6.12	6.48	6.84
		FEB	4.24	4.77	4.78	4.80	5.10	5.25	5.45
		MAR	4.20	4.49	4.51	4.50	4.63	4.68	4.68
		APR	4.07	4.28	4.36	4.35	4.36	4.40	4.33
		MAY	4.94	5.40	5.42	5.49	5.53	5.52	5.45
		JUN	5.35	6.14	6.20	6.11	6.55	6.52	6.54
		JUL	6.81	8.07	8.14	8.09	8.58	8.74	8.73
		AUG	8.35	10.56	10.56	10.62	11.28	11.49	11.51
		SEP	7.60	9.67	9.83	9.72	10.53	11.20	11.56
		OCT	7.42	9.89	9.86	9.89	11.37	12.16	12.80
		NOV	7.77	10.70	10.68	10.74	12.78	13.60	14.70
		DEC	5.78	7.85	7.83	7.96	9.35	10.49	11.76
		Mean	5.94	7.28	7.31	7.33	8.01	8.38	8.70
	DOC flux (g of OC m^{-2} $month^{-1}$)	**JAN**	0.36	0.41	0.41	0.41	0.45	0.45	0.48

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Ouse catchment	DOC flux (g of OC m^{-2} $month^{-1}$)	FEB	0.25	0.29	0.29	0.29	0.31	0.32	0.33
		MAR	0.25	0.25	0.25	0.25	0.25	0.25	0.24
		APR	0.20	0.19	0.19	0.19	0.18	0.17	0.16
		MAY	0.22	0.19	0.18	0.19	0.17	0.15	0.14
		JUN	0.18	0.16	0.15	0.15	0.14	0.13	0.12
		JUL	0.22	0.20	0.20	0.20	0.19	0.17	0.15
		AUG	0.22	0.20	0.20	0.21	0.19	0.16	0.14
		SEP	0.19	0.18	0.19	0.18	0.17	0.16	0.14
		OCT	0.21	0.21	0.21	0.20	0.19	0.19	0.17
		NOV	0.40	0.41	0.40	0.39	0.41	0.37	0.35
		DEC	0.40	0.51	0.51	0.51	0.59	0.62	0.68
		Total	3.09	3.19	3.19	3.17	3.24	3.14	3.11
Derwent (Derbyshire)	Discharge (m^3 s^{-1})	JAN	38.62	37.84	38.54	37.82	38.60	37.12	36.77
		FEB	32.59	33.57	34.02	34.03	35.33	35.70	36.17
		MAR	27.73	27.83	27.36	27.30	27.45	27.94	27.83
		APR	24.00	22.57	21.95	21.91	21.00	20.69	19.59
		MAY	22.61	18.82	18.45	18.53	16.97	16.06	14.93
		JUN	23.50	17.64	17.33	16.87	15.63	14.02	13.11
		JUL	22.96	17.67	17.33	17.05	15.44	13.68	12.42
		AUG	16.21	13.12	12.87	13.01	11.70	10.68	9.73
		SEP	14.39	11.88	11.73	11.85	10.33	9.36	8.50
		OCT	16.19	13.08	12.87	12.98	11.28	10.56	9.69
		NOV	27.15	21.93	21.66	21.21	19.27	16.97	15.47
		DEC	35.43	32.86	32.71	31.99	31.52	29.44	28.30
		Mean	25.11	22.40	22.23	22.05	21.21	20.19	19.38
	DOC concentration (mg L^{-1})	JAN	2.86	3.10	3.18	3.18	3.30	3.38	3.44
		FEB	2.72	2.79	2.90	2.91	2.96	3.02	3.07

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Derwent (Derbyshire)	**DOC concentration (mg L^{-1})**	**MAR**	2.78	2.74	2.90	2.85	2.91	2.93	2.93
		APR	2.88	2.79	3.02	2.96	3.00	3.00	2.96
		MAY	3.34	3.16	3.40	3.41	3.42	3.45	3.40
		JUN	3.52	3.54	3.77	3.70	3.69	3.64	3.66
		JUL	3.86	3.90	4.02	4.00	4.01	4.02	4.21
		AUG	3.96	3.90	3.97	3.96	4.10	4.12	3.95
		SEP	3.61	3.51	3.67	3.64	3.60	3.57	3.41
		OCT	3.51	3.42	3.59	3.54	3.57	3.53	3.43
		NOV	3.49	3.55	3.64	3.62	3.66	3.60	3.50
		DEC	3.10	3.37	3.44	3.44	3.54	3.60	3.60
		Mean	3.30	3.31	3.46	3.43	3.48	3.49	3.47
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	0.24	0.26	0.27	0.26	0.28	0.28	0.28
		FEB	0.20	0.21	0.22	0.22	0.23	0.24	0.24
		MAR	0.17	0.17	0.17	0.17	0.18	0.18	0.18
		APR	0.15	0.14	0.15	0.14	0.14	0.14	0.13
		MAY	0.17	0.13	0.14	0.14	0.13	0.12	0.11
		JUN	0.18	0.14	0.14	0.14	0.13	0.11	0.11
		JUL	0.20	0.15	0.15	0.15	0.14	0.12	0.12
		AUG	0.14	0.11	0.11	0.11	0.11	0.10	0.08
		SEP	0.11	0.09	0.09	0.09	0.08	0.07	0.06
		OCT	0.13	0.10	0.10	0.10	0.09	0.08	0.07
		NOV	0.21	0.17	0.17	0.17	0.16	0.13	0.12
		DEC	0.24	0.24	0.25	0.24	0.25	0.23	0.22
		Total	2.13	1.91	1.97	1.94	1.89	1.81	1.73
Severn catchment	**Discharge (m^{3} s^{-1})**	**JAN**	90.38	90.89	92.15	90.84	91.64	88.24	85.73
		FEB	66.46	67.66	68.10	68.24	68.90	69.58	69.36
		MAR	53.29	54.05	53.17	53.04	52.19	52.17	50.78

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Severn catchment	Discharge (m^3 s^{-1})	APR	49.17	42.76	41.74	41.44	37.47	35.20	31.82
		MAY	53.80	38.41	37.28	37.50	32.03	28.72	25.76
		JUN	35.55	25.69	25.04	24.73	21.63	18.95	17.19
		JUL	34.52	22.81	22.09	22.03	18.96	16.44	14.23
		AUG	23.29	16.32	15.89	16.15	13.45	11.58	9.93
		SEP	20.88	14.79	14.52	14.68	11.80	10.03	8.46
		OCT	27.55	19.45	19.12	19.13	15.15	12.58	10.39
		NOV	59.67	44.66	44.09	42.85	36.61	29.14	23.07
		DEC	79.67	76.44	76.92	74.67	72.39	66.82	62.08
		Mean	49.52	42.83	42.51	42.11	39.35	36.62	34.07
	DOC concentration (mg L^{-1})	JAN	3.96	6.02	6.05	6.08	7.77	8.21	8.60
		FEB	3.43	4.83	4.84	4.87	5.85	6.15	6.40
		MAR	3.47	4.56	4.57	4.58	5.23	5.34	5.45
		APR	3.34	4.08	4.16	4.18	4.57	4.52	4.47
		MAY	3.67	4.52	4.56	4.60	5.10	5.01	4.93
		JUN	3.90	4.55	4.71	4.74	5.12	4.97	5.01
		JUL	4.67	5.35	5.41	5.50	5.83	5.71	5.63
		AUG	5.21	5.89	5.80	5.81	6.08	5.86	5.55
		SEP	4.81	5.68	5.78	5.75	6.00	5.72	5.42
		OCT	4.74	6.16	6.24	6.21	7.35	7.08	6.59
		NOV	5.06	7.54	7.46	7.39	9.50	9.32	9.05
		DEC	4.32	7.02	7.00	7.00	9.66	10.19	10.52
		Mean	4.22	5.52	5.55	5.56	6.50	6.51	6.47
	DOC flux (g of OC m^{-2} month^{-1})	JAN	0.46	0.70	0.71	0.71	0.91	0.93	0.94
		FEB	0.29	0.42	0.42	0.43	0.52	0.55	0.57
		MAR	0.24	0.32	0.31	0.31	0.35	0.36	0.35
		APR	0.21	0.22	0.22	0.22	0.22	0.20	0.18

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Severn catchment	**DOC flux (g of OC m^{-2} month^{-1})**	**MAY**	0.25	0.22	0.22	0.22	0.21	0.18	0.16
		JUN	0.18	0.15	0.15	0.15	0.14	0.12	0.11
		JUL	0.21	0.16	0.15	0.16	0.14	0.12	0.10
		AUG	0.16	0.12	0.12	0.12	0.10	0.09	0.07
		SEP	0.13	0.11	0.11	0.11	0.09	0.07	0.06
		OCT	0.17	0.15	0.15	0.15	0.14	0.11	0.09
		NOV	0.39	0.43	0.42	0.41	0.45	0.35	0.27
		DEC	0.44	0.69	0.69	0.67	0.89	0.87	0.84
		Total	3.11	3.69	3.68	3.65	4.17	3.95	3.74
Wye catchment	**Discharge (m^3 s^{-1})**	**JAN**	137.29	128.96	132.16	128.29	135.59	128.04	131.07
		FEB	87.95	93.72	94.35	94.06	96.23	96.55	96.43
		MAR	97.30	92.86	90.48	88.15	85.79	86.16	84.39
		APR	65.53	60.04	58.54	58.09	55.09	53.43	51.11
		MAY	70.57	63.11	61.78	62.14	58.04	53.93	50.90
		JUN	55.23	46.24	45.54	44.54	42.58	38.53	36.13
		JUL	61.26	51.06	50.08	49.96	45.84	41.00	36.58
		AUG	46.17	39.06	37.98	38.23	34.60	31.28	28.05
		SEP	51.53	42.75	41.72	41.88	35.09	31.20	27.24
		OCT	54.29	44.42	43.78	43.78	38.26	36.70	32.76
		NOV	119.98	110.48	108.26	104.02	99.01	94.92	89.58
		DEC	147.87	151.72	153.09	147.05	154.22	151.80	156.43
		Mean	82.91	77.04	76.48	75.02	73.36	70.29	68.39
	DOC concentration (mg L^{-1})	**JAN**	2.53	2.50	2.53	2.56	2.72	2.81	2.92
		FEB	2.37	2.20	2.19	2.22	2.30	2.36	2.39
		MAR	2.43	2.17	2.15	2.18	2.23	2.25	2.28

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Wye catchment	DOC concentration (mg L^{-1})	APR	2.52	2.10	2.09	2.19	2.17	2.14	2.21
		MAY	3.06	2.79	2.79	2.83	2.88	2.85	2.89
		JUN	3.26	3.05	3.05	3.08	3.15	3.09	3.11
		JUL	3.54	3.55	3.55	3.61	3.68	3.68	3.68
		AUG	3.71	3.74	3.70	3.71	3.74	3.67	3.62
		SEP	3.42	3.53	3.50	3.56	3.62	3.70	3.75
		OCT	4.14	4.60	4.62	4.64	4.99	5.29	5.51
		NOV	4.07	4.78	4.81	4.80	5.35	5.67	6.09
		DEC	3.03	3.43	3.48	3.51	3.92	4.17	4.48
		Mean	3.17	3.20	3.20	3.24	3.40	3.47	3.58
	DOC flux (g of OC m^{-2} month^{-1})	JAN	0.22	0.21	0.22	0.21	0.24	0.23	0.25
		FEB	0.13	0.13	0.13	0.14	0.14	0.15	0.15
		MAR	0.15	0.13	0.13	0.12	0.12	0.13	0.12
		APR	0.11	0.08	0.08	0.08	0.08	0.07	0.07
		MAY	0.14	0.11	0.11	0.11	0.11	0.10	0.10
		JUN	0.12	0.09	0.09	0.09	0.09	0.08	0.07
		JUL	0.14	0.12	0.11	0.12	0.11	0.10	0.09
		AUG	0.11	0.09	0.09	0.09	0.08	0.07	0.07
		SEP	0.11	0.10	0.09	0.10	0.08	0.07	0.07
		OCT	0.15	0.13	0.13	0.13	0.12	0.13	0.12
		NOV	0.32	0.34	0.34	0.32	0.34	0.35	0.35
		DEC	0.29	0.34	0.34	0.33	0.39	0.41	0.45
		Total	1.99	1.88	1.87	1.85	1.91	1.88	1.90
Ribble catchment	Discharge (m^3 s^{-1})	JAN	70.28	68.15	69.81	68.49	70.55	67.67	70.02
		FEB	51.04	51.96	52.11	52.41	54.88	56.76	57.94
		MAR	40.88	41.54	40.25	39.19	38.81	39.22	38.70
		APR	31.79	29.96	29.31	29.69	28.47	27.66	26.82

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Ribble catchment	**Discharge (m^3 s^{-1})**	**MAY**	33.28	28.88	28.42	28.58	26.42	24.36	22.97
		JUN	25.53	20.77	20.50	20.02	18.77	16.82	15.47
		JUL	31.66	25.96	25.41	25.80	22.98	20.70	18.06
		AUG	28.99	22.25	21.24	21.51	18.76	16.27	14.25
		SEP	38.50	31.67	32.48	31.55	26.36	24.09	21.61
		OCT	41.27	36.63	36.69	36.44	32.75	33.12	30.61
		NOV	62.42	61.07	60.31	58.38	58.26	57.48	56.63
		DEC	81.28	85.88	85.65	84.73	89.60	88.97	97.17
		Mean	44.74	42.06	41.85	41.40	40.55	39.43	39.19
	DOC concentration (mg L^{-1})	**JAN**	4.42	5.26	5.28	5.31	5.70	5.96	6.21
		FEB	4.16	4.85	4.86	4.89	5.28	5.48	5.68
		MAR	4.14	4.72	4.72	4.72	5.01	5.15	5.28
		APR	4.19	4.63	4.63	4.69	4.91	5.01	5.13
		MAY	5.42	6.04	6.04	6.08	6.40	6.47	6.65
		JUN	5.34	5.96	5.96	5.91	6.28	6.22	6.20
		JUL	7.26	8.04	8.04	8.08	8.33	8.47	8.35
		AUG	8.31	9.10	8.95	8.97	9.17	8.96	8.77
		SEP	7.36	8.50	8.60	8.56	8.98	9.30	9.51
		OCT	6.91	7.94	7.94	7.99	8.52	9.01	9.27
		NOV	6.42	7.49	7.51	7.55	8.11	8.43	8.82
		DEC	4.61	5.41	5.44	5.49	5.88	6.15	6.32
		Mean	5.71	6.49	6.50	6.52	6.88	7.05	7.18
	DOC flux (g of OC m^{-2} $month^{-1}$)	**JAN**	0.71	0.81	0.84	0.83	0.91	0.92	0.99
		FEB	0.48	0.57	0.58	0.58	0.66	0.71	0.75
		MAR	0.38	0.44	0.43	0.42	0.44	0.46	0.46
		APR	0.30	0.31	0.31	0.32	0.32	0.31	0.31
		MAY	0.41	0.40	0.39	0.39	0.38	0.36	0.35

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Ribble catchment	**DOC flux (g of OC m^{-2} month^{-1})**	**JUN**	0.31	0.28	0.28	0.27	0.27	0.24	0.22
		JUL	0.52	0.47	0.46	0.47	0.43	0.40	0.34
		AUG	0.55	0.46	0.43	0.44	0.39	0.33	0.28
		SEP	0.64	0.61	0.63	0.61	0.54	0.51	0.47
		OCT	0.65	0.66	0.66	0.66	0.63	0.68	0.64
		NOV	0.91	1.04	1.03	1.00	1.07	1.10	1.13
		DEC	0.85	1.05	1.06	1.06	1.20	1.24	1.39
		Total	6.71	7.12	7.09	7.05	7.25	7.25	7.34
Derwent (Cumbria) catchment	**Discharge (m^3 s^{-1})**	**JAN**	25.79	27.10	27.81	27.46	30.23	30.18	32.06
		FEB	16.66	17.60	17.67	17.75	18.94	19.54	20.10
		MAR	13.17	13.58	13.57	13.44	13.76	14.19	14.34
		APR	11.78	11.64	11.52	11.66	11.50	11.35	11.12
		MAY	11.91	10.63	10.48	10.62	9.84	9.11	8.52
		JUN	8.66	6.98	6.89	6.77	6.30	5.62	5.22
		JUL	11.17	8.79	8.52	8.77	7.31	6.55	5.74
		AUG	12.33	9.24	8.81	9.01	8.77	6.27	5.48
		SEP	10.33	8.02	8.09	7.94	6.95	5.92	5.26
		OCT	17.05	14.69	14.95	14.82	13.09	13.30	12.13
		NOV	27.65	28.76	28.58	27.87	27.99	28.17	28.11
		DEC	30.20	33.40	34.13	33.83	36.63	36.97	41.27
		Mean	16.39	15.87	15.92	15.83	15.94	15.60	15.78
	DOC concentration (mg L^{-1})	**JAN**	1.36	1.40	1.40	1.39	1.38	1.43	1.43
		FEB	1.27	1.30	1.30	1.29	1.28	1.32	1.33
		MAR	1.21	1.23	1.23	1.22	1.21	1.25	1.25
		APR	1.21	1.22	1.23	1.21	1.19	1.23	1.25
		MAY	1.33	1.38	1.37	1.37	1.34	1.40	1.44
		JUN	1.54	1.61	1.61	1.59	1.57	1.65	1.68

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Derwent (Cumbria) catchment	**DOC concentration (mg L^{-1})**	**JUL**	1.92	2.05	2.07	2.05	2.01	2.17	2.20
		AUG	2.36	2.62	2.62	2.60	2.59	2.82	2.93
		SEP	2.43	2.69	2.68	2.69	2.67	2.97	3.10
		OCT	2.28	2.60	2.59	2.61	2.64	2.94	3.11
		NOV	1.86	2.06	2.06	2.08	2.11	2.29	2.40
		DEC	1.52	1.60	1.60	1.61	1.61	1.69	1.72
		Mean	1.69	1.81	1.81	1.81	1.80	1.93	1.99
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	0.39	0.42	0.43	0.42	0.46	0.47	0.51
		FEB	0.23	0.25	0.25	0.25	0.27	0.28	0.29
		MAR	0.18	0.18	0.18	0.18	0.18	0.20	0.20
		APR	0.16	0.16	0.16	0.16	0.15	0.15	0.15
		MAY	0.17	0.16	0.16	0.16	0.15	0.14	0.14
		JUN	0.15	0.12	0.12	0.12	0.11	0.10	0.10
		JUL	0.24	0.20	0.19	0.20	0.16	0.16	0.14
		AUG	0.32	0.27	0.25	0.26	0.25	0.20	0.18
		SEP	0.28	0.24	0.24	0.24	0.20	0.19	0.18
		OCT	0.43	0.42	0.43	0.43	0.38	0.43	0.42
		NOV	0.57	0.65	0.65	0.64	0.65	0.71	0.74
		DEC	0.50	0.59	0.60	0.60	0.65	0.69	0.78
		Total	3.61	3.66	3.67	3.65	3.62	3.73	3.82
Eamont catchment	**Discharge (m^{3} s^{-1})**	**JAN**	36.44	38.13	39.23	38.72	41.47	41.11	42.98
		FEB	23.14	24.36	24.51	24.60	25.43	26.11	26.52
		MAR	18.53	17.62	17.61	17.38	17.02	17.23	16.99
		APR	17.47	14.94	14.78	14.84	13.98	13.62	13.02
		MAY	17.30	11.46	11.29	11.43	10.34	9.48	8.82
		JUN	13.57	8.91	8.81	8.63	7.95	7.13	6.61
		JUL	16.47	10.25	9.95	10.23	8.73	7.93	7.04

Catchment	Items	Month	Baseline	2030s B1	2030s A1B	2030s A1F1	2090s B1	2090s A1B	2090s A1F1
Eamont catchment	**Discharge (m^3 s^{-1})**	**AUG**	16.32	9.40	9.00	9.21	7.85	7.00	6.28
		SEP	12.84	7.17	7.21	7.12	6.26	5.82	5.37
		OCT	22.00	12.56	12.82	12.66	11.05	11.29	10.21
		NOV	37.55	31.79	31.64	30.72	30.28	29.97	29.09
		DEC	39.42	39.89	40.75	40.25	42.56	42.42	46.73
		Mean	22.59	18.87	18.97	18.82	18.58	18.26	18.31
	DOC concentration (mg L^{-1})	**JAN**	1.79	1.84	1.83	1.84	1.82	1.82	1.79
		FEB	1.72	1.73	1.73	1.74	1.72	1.70	1.68
		MAR	1.76	1.75	1.75	1.75	1.75	1.72	1.70
		APR	1.73	1.74	1.74	1.74	1.74	1.73	1.69
		MAY	2.00	2.06	2.07	2.07	2.15	2.12	2.10
		JUN	2.18	2.31	2.33	2.31	2.35	2.41	2.39
		JUL	2.73	3.02	2.98	2.98	3.13	3.07	3.29
		AUG	2.79	3.13	3.16	3.13	3.21	3.28	3.30
		SEP	2.68	3.01	2.98	2.98	3.12	3.27	3.34
		OCT	2.68	3.14	3.13	3.18	3.33	3.51	3.65
		NOV	2.12	2.40	2.40	2.42	2.49	2.54	2.61
		DEC	1.87	2.01	2.01	2.02	2.02	2.03	2.02
		Mean	2.17	2.35	2.35	2.35	2.40	2.43	2.46
	DOC flux (g of OC m^{-2} $month^{-1}$)	**JAN**	0.43	0.46	0.47	0.47	0.50	0.49	0.50
		FEB	0.26	0.28	0.28	0.28	0.29	0.29	0.29
		MAR	0.21	0.20	0.20	0.20	0.19	0.19	0.19
		APR	0.20	0.17	0.17	0.17	0.16	0.15	0.14
		MAY	0.23	0.15	0.15	0.16	0.15	0.13	0.12
		JUN	0.19	0.13	0.13	0.13	0.12	0.11	0.10
		JUL	0.29	0.20	0.19	0.20	0.18	0.16	0.15
		AUG	0.30	0.19	0.19	0.19	0.16	0.15	0.14

Catchment	**Items**	**Month**	**Baseline**	**2030s B1**	**2030s A1B**	**2030s A1F1**	**2090s B1**	**2090s A1B**	**2090s A1F1**
Eamont catchment	**DOC flux (g of OC m^{-2} $month^{-1}$)**	**SEP**	0.23	0.14	0.14	0.14	0.13	0.12	0.12
		OCT	0.39	0.26	0.26	0.26	0.24	0.26	0.24
		NOV	0.52	0.50	0.50	0.49	0.49	0.50	0.50
		DEC	0.48	0.52	0.54	0.53	0.56	0.56	0.62
		Total	3.72	3.22	3.22	3.21	3.17	3.13	3.12

Table F.5 Projected changes to monthly averaged flow, DOC concentration, and DOC flux for climate change scenarios compared with baseline at all nine catchments.

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
Tyne catchment	Discharge (m^3 s^{-1})	JAN	-4.03	-0.22	-0.48	2.79	1.49	0.99
		FEB	-0.05	1.52	1.46	3.34	3.57	0.88
		MAR	7.30	-8.22	-8.48	-15.05	-16.18	-22.59
		APR	2.75	-17.36	-17.12	-24.04	-27.14	-36.80
		MAY	-6.55	-31.44	-30.28	-40.82	-47.49	-58.40
		JUN	-15.19	-46.77	-47.36	-56.74	-64.54	-71.41
		JUL	-17.37	-51.57	-51.47	-61.74	-69.81	-75.89
		AUG	-40.26	-66.59	-66.06	-73.49	-77.27	-79.60
		SEP	-29.93	-50.37	-51.34	-64.21	-71.03	-73.94
		OCT	-31.38	-52.30	-52.93	-60.87	-65.36	-66.25
		NOV	-7.39	-30.68	-33.03	-40.59	-49.88	-46.00
		DEC	5.05	-4.55	-6.05	-5.63	-11.13	-5.27
		Mean	-10.14	-26.93	-27.42	-32.89	-37.59	-40.12
	DOC concentration (mg L^{-1})	JAN	30.35	67.58	69.58	103.33	125.17	127.49
		FEB	23.12	47.13	48.51	68.82	80.88	85.30
		MAR	25.15	32.80	33.46	44.74	50.06	47.34
		APR	16.26	18.87	19.23	24.49	26.46	21.91
		MAY	7.34	7.02	8.05	8.07	6.62	0.09
		JUN	3.35	1.37	0.42	1.49	-2.39	-6.45
		JUL	2.92	8.66	8.36	8.23	5.75	3.79
Tyne catchment	DOC concentration (mg L^{-1})	AUG	-9.66	-9.14	-8.65	-11.51	-12.03	-7.87
		SEP	-5.33	-0.51	-1.13	3.84	4.68	8.10
		OCT	-0.28	1.70	1.56	5.07	8.00	12.56
		NOV	35.49	55.84	54.93	70.75	69.59	77.47

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	42.31	89.69	91.50	133.92	152.27	160.32
		Mean	13.30	25.69	26.02	36.97	41.12	43.03
	DOC flux (g of OC m^{-2} $month^{-1}$)	**JAN**	25.09	67.21	68.76	109.01	128.52	129.75
		FEB	23.05	49.37	50.68	74.45	87.34	86.94
		MAR	34.28	21.88	22.14	22.96	25.78	14.05
		APR	19.46	-1.77	-1.18	-5.44	-7.86	-22.96
		MAY	0.31	-26.63	-24.67	-36.04	-44.01	-58.36
		JUN	-12.35	-46.04	-47.14	-56.09	-65.39	-73.26
		JUL	-14.95	-47.37	-47.41	-58.59	-68.08	-74.97
		AUG	-46.04	-69.65	-68.99	-76.54	-80.01	-81.20
		SEP	-33.67	-50.62	-51.89	-62.83	-69.68	-71.82
		OCT	-31.58	-51.49	-52.20	-58.89	-62.58	-62.01
		NOV	25.48	8.04	3.76	1.45	-15.01	-4.16
		DEC	49.50	81.05	79.91	120.75	124.19	146.60
		Total	4.33	-1.49	-1.98	3.56	1.69	2.27
Tees catchment	**Discharge (m^3 s^{-1})**	**JAN**	5.20	7.17	6.81	11.60	10.51	11.70
		FEB	8.46	9.15	9.48	9.13	10.00	10.27
		MAR	-7.25	-9.19	-9.71	-14.81	-15.93	-17.33
		APR	-16.87	-18.10	-17.36	-23.41	-26.64	-31.51
		MAY	-17.74	-19.57	-18.12	-29.34	-37.70	-45.01
		JUN	-27.63	-28.84	-29.95	-39.05	-47.55	-53.35
		JUL	-29.25	-30.73	-29.64	-41.84	-50.89	-58.54
Tees catchment	**Discharge (m^3 s^{-1})**	**AUG**	-38.84	-39.75	-38.81	-49.99	-56.33	-60.26
		SEP	-30.84	-29.55	-31.03	-50.77	-58.31	-63.55
		OCT	-36.32	-36.62	-37.75	-46.99	-51.77	-57.24
		NOV	-13.54	-13.14	-15.42	-20.39	-29.30	-36.88

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
Tees catchment		**DEC**	0.96	0.98	-0.06	1.03	-1.52	0.61
		Mean	-13.48	-13.65	-14.10	-19.59	-24.25	-27.57
	DOC concentration (mg L^{-1})	**JAN**	31.75	31.50	32.63	49.78	61.86	72.15
		FEB	19.23	18.95	19.28	28.71	33.20	38.16
		MAR	13.48	13.54	13.59	20.11	20.83	23.54
		APR	13.11	13.82	14.13	21.20	23.43	26.77
		MAY	15.64	15.75	16.18	24.06	24.26	26.31
		JUN	13.72	13.36	13.61	20.33	19.66	19.89
		JUL	21.75	22.44	22.34	31.45	33.44	34.40
		AUG	20.23	19.75	20.25	28.18	27.71	29.91
		SEP	17.51	17.95	17.38	28.43	33.20	36.28
		OCT	21.56	21.07	20.75	33.05	36.38	40.99
		NOV	47.82	48.18	49.04	73.08	78.87	85.94
		DEC	47.15	47.20	49.64	81.21	101.33	123.04
		Mean	23.54	23.58	23.93	36.30	40.32	45.08
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	38.60	40.93	41.66	67.15	78.88	92.30
		FEB	29.33	29.83	30.58	40.46	46.53	52.35
		MAR	5.25	3.10	2.56	2.32	1.58	2.13
		APR	-5.97	-6.78	-5.68	-7.17	-9.46	-13.18
		MAY	-4.88	-6.90	-4.88	-12.34	-22.58	-30.54
		JUN	-17.69	-19.33	-20.41	-26.66	-37.24	-44.07
		JUL	-13.87	-15.19	-13.92	-23.55	-34.47	-44.27
	DOC flux (g of OC m^{-2} month^{-1})	**AUG**	-26.46	-27.85	-26.42	-35.89	-44.23	-48.37
		SEP	-18.72	-16.90	-19.04	-36.78	-44.47	-50.32
		OCT	-22.58	-23.27	-24.83	-29.47	-34.22	-39.71
		NOV	27.81	28.71	26.05	37.78	26.46	17.37

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	48.56	48.65	49.56	83.08	98.26	124.39
		Total	6.26	6.13	5.85	9.47	6.48	5.89
Ouse catchment	Discharge (m^3 s^{-1})	JAN	-2.64	-1.16	-2.68	-2.06	-6.65	-6.49
		FEB	1.07	1.85	1.85	2.67	2.50	2.28
		MAR	-6.46	-7.88	-8.18	-10.66	-11.03	-13.50
		APR	-10.27	-12.05	-11.85	-17.66	-20.73	-26.07
		MAY	-22.19	-23.71	-22.67	-31.50	-37.65	-42.95
		JUN	-25.93	-27.11	-28.27	-35.09	-43.38	-48.34
		JUL	-22.55	-23.70	-24.50	-32.41	-41.07	-47.88
		AUG	-25.07	-26.47	-25.25	-36.17	-44.57	-51.70
		SEP	-25.14	-24.63	-24.82	-36.78	-43.97	-50.34
		OCT	-25.75	-25.31	-26.48	-39.21	-45.00	-51.32
		NOV	-26.29	-26.36	-28.69	-37.39	-46.53	-53.23
		DEC	-4.40	-4.23	-5.95	-7.21	-14.00	-15.04
		Mean	-13.15	-13.44	-14.14	-19.00	-24.16	-27.73
	DOC concentration (mg L^{-1})	JAN	17.95	18.14	18.92	29.35	36.94	44.60
		FEB	12.39	12.68	13.21	20.29	23.89	28.39
		MAR	7.07	7.32	7.14	10.23	11.49	11.53
		APR	4.99	7.17	6.93	6.99	8.09	6.32
		MAY	9.39	9.84	11.15	12.05	11.83	10.44
		JUN	14.91	15.95	14.23	22.49	21.90	22.41
		JUL	18.46	19.57	18.84	26.00	28.38	28.22
Ouse catchment	DOC concentration (mg L^{-1})	AUG	26.41	26.46	27.11	34.99	37.53	37.83
		SEP	27.34	29.41	27.97	38.62	47.40	52.21
		OCT	33.40	32.92	33.39	53.29	64.04	72.61
		NOV	37.70	37.45	38.23	64.43	74.94	89.10

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	35.86	35.60	37.88	61.91	81.64	103.55
		Mean	22.67	23.18	23.38	34.98	41.10	46.47
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	14.84	16.76	15.73	26.68	27.84	35.21
		FEB	13.59	14.77	15.31	23.50	26.98	31.31
		MAR	0.15	-1.14	-1.62	-1.52	-0.80	-3.54
		APR	-5.79	-5.74	-5.74	-11.90	-14.32	-21.40
		MAY	-14.88	-16.21	-14.05	-23.25	-30.27	-36.99
		JUN	-14.89	-15.49	-18.06	-20.49	-30.98	-36.77
		JUL	-8.25	-8.77	-10.28	-14.83	-24.34	-33.18
		AUG	-5.29	-7.02	-4.99	-13.83	-23.77	-33.43
		SEP	-4.67	-2.47	-3.79	-12.36	-17.42	-24.41
		OCT	-0.94	-0.71	-1.93	-6.81	-9.77	-15.97
		NOV	1.49	1.22	-1.43	2.94	-6.46	-11.56
		DEC	29.88	29.86	29.68	50.24	56.21	72.93
		Total	3.23	3.27	2.66	4.80	1.66	0.69
Derwent (Derbyshire)	**Discharge (m^3 s^{-1})**	**JAN**	-2.04	-0.22	-2.09	-0.05	-3.88	-4.79
		FEB	2.99	4.38	4.40	8.39	9.54	10.98
		MAR	0.36	-1.33	-1.53	-0.99	0.76	0.39
		APR	-5.95	-8.54	-8.69	-12.48	-13.79	-18.36
		MAY	-16.76	-18.41	-18.04	-24.93	-28.94	-33.96
		JUN	-24.93	-26.25	-28.21	-33.49	-40.32	-44.23
		JUL	-23.03	-24.51	-25.72	-32.72	-40.40	-45.92
Derwent (Derbyshire)	**Discharge (m^3 s^{-1})**	**AUG**	-19.11	-20.60	-19.78	-27.84	-34.11	-39.98
		SEP	-17.42	-18.50	-17.61	-28.21	-34.95	-40.96
		OCT	-19.17	-20.52	-19.84	-30.30	-34.79	-40.14
		NOV	-19.22	-20.20	-21.86	-29.02	-37.51	-43.02

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
Derwent (Derbyshire)		**DEC**	-7.24	-7.68	-9.69	-11.03	-16.90	-20.11
		Mean	-10.81	-11.47	-12.22	-15.54	-19.62	-22.85
	DOC concentration (mg L^{-1})	**JAN**	8.37	11.14	11.19	15.49	18.18	20.09
		FEB	2.41	6.50	6.82	8.63	11.10	12.89
		MAR	-1.49	4.39	2.66	4.66	5.39	5.54
		APR	-3.23	4.81	2.48	3.96	4.18	2.68
		MAY	-5.36	1.80	2.04	2.43	3.21	1.93
		JUN	0.60	7.26	5.05	4.93	3.43	4.16
		JUL	1.08	4.04	3.52	3.88	4.21	9.05
		AUG	-1.40	0.44	0.09	3.63	4.20	-0.18
		SEP	-2.84	1.50	0.62	-0.35	-1.32	-5.53
		OCT	-2.66	2.12	0.86	1.71	0.53	-2.33
		NOV	1.78	4.34	3.91	5.01	3.09	0.45
		DEC	8.60	10.85	10.94	14.32	16.12	16.23
		Mean	0.33	4.70	3.95	5.39	5.62	4.91
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	6.16	10.89	8.86	15.43	13.60	14.34
		FEB	5.48	11.17	11.52	17.75	21.69	25.29
		MAR	-1.13	3.01	1.09	3.62	6.19	5.95
		APR	-8.99	-4.15	-6.42	-9.01	-10.18	-16.18
		MAY	-21.22	-16.94	-16.38	-23.11	-26.66	-32.69
		JUN	-24.48	-20.90	-24.58	-30.21	-38.28	-41.91
		JUL	-22.20	-21.46	-23.10	-30.12	-37.89	-41.03
	DOC flux (g of OC m^{-2} month^{-1})	**AUG**	-20.25	-20.25	-19.70	-25.22	-31.34	-40.09
		SEP	-19.77	-17.27	-17.10	-28.46	-35.81	-44.22
		OCT	-21.31	-18.83	-19.15	-29.11	-34.44	-41.54
		NOV	-17.78	-16.74	-18.81	-25.47	-35.58	-42.76

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	0.73	2.34	0.19	1.71	-3.50	-7.15
		Total	-10.60	-7.60	-8.95	-11.29	-15.39	-19.05
Severn catchment	**Discharge (m^3 s^{-1})**	**JAN**	0.56	1.96	0.50	1.39	-2.37	-5.15
		FEB	1.81	2.47	2.68	3.67	4.70	4.36
		MAR	1.43	-0.22	-0.46	-2.06	-2.11	-4.71
		APR	-13.04	-15.12	-15.72	-23.80	-28.42	-35.30
		MAY	-28.59	-30.70	-30.30	-40.47	-46.61	-52.11
		JUN	-27.73	-29.56	-30.42	-39.17	-46.68	-51.64
		JUL	-33.92	-36.00	-36.19	-45.08	-52.37	-58.77
		AUG	-29.93	-31.80	-30.67	-42.25	-50.28	-57.37
		SEP	-29.19	-30.45	-29.69	-43.47	-51.97	-59.47
		OCT	-29.42	-30.62	-30.57	-45.02	-54.35	-62.28
		NOV	-25.15	-26.12	-28.19	-38.65	-51.17	-61.34
		DEC	-4.05	-3.45	-6.28	-9.14	-16.13	-22.08
		Mean	-13.51	-14.16	-14.97	-20.54	-26.05	-31.21
	DOC concentration (mg L^{-1})	**JAN**	52.13	52.73	53.65	96.25	107.34	117.08
		FEB	40.85	41.18	42.12	70.45	79.26	86.46
		MAR	31.25	31.64	31.93	50.56	53.66	56.88
		APR	22.42	24.81	25.23	37.04	35.46	33.86
		MAY	23.13	24.12	25.26	38.92	36.46	34.21
		JUN	16.62	20.66	21.43	31.26	27.43	28.40
Severn catchment	**DOC concentration (mg L^{-1})**	**JUL**	14.61	15.77	17.75	24.73	22.33	20.44
		AUG	12.96	11.37	11.54	16.63	12.43	6.43
		SEP	18.01	20.19	19.54	24.65	18.74	12.64
		OCT	30.04	31.68	31.06	55.08	49.36	39.16
		NOV	48.91	47.33	46.11	87.74	84.17	78.73

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	62.60	62.21	62.13	123.80	136.10	143.75
		Mean	30.88	31.63	31.91	54.31	54.34	53.40
	DOC flux (g of OC m^{-2} $month^{-1}$)	**JAN**	52.98	55.72	54.42	98.97	102.43	105.91
		FEB	43.39	44.67	45.93	76.71	87.69	94.59
		MAR	33.12	31.35	31.32	47.45	50.41	49.49
		APR	6.46	5.94	5.54	4.43	-3.04	-13.39
		MAY	-12.08	-13.98	-12.69	-17.30	-27.15	-35.73
		JUN	-15.73	-15.01	-15.52	-20.15	-32.06	-37.91
		JUL	-24.27	-25.90	-24.87	-31.50	-41.73	-50.34
		AUG	-20.85	-24.04	-22.67	-32.65	-44.10	-54.63
		SEP	-16.44	-16.41	-15.95	-29.54	-42.97	-54.35
		OCT	-8.23	-8.64	-9.00	-14.73	-31.82	-47.51
		NOV	11.46	8.85	4.93	15.18	-10.07	-30.91
		DEC	56.01	56.62	51.95	103.34	98.02	89.94
		Total	18.52	18.23	17.20	33.89	27.06	20.28
		JAN	-6.07	-3.74	-6.55	-1.24	-6.74	-4.53
		FEB	6.56	7.28	6.95	9.41	9.79	9.64
Wye catchment	**Discharge (m^3 s^{-1})**	**MAR**	-4.56	-7.01	-9.40	-11.82	-11.45	-13.26
		APR	-8.37	-10.66	-11.35	-15.93	-18.47	-22.00
		MAY	-10.57	-12.46	-11.95	-17.76	-23.58	-27.88
		JUN	-16.28	-17.55	-19.35	-22.92	-30.25	-34.59
		JUL	-16.66	-18.25	-18.45	-25.17	-33.06	-40.29
Wye catchment	**Discharge (m^3 s^{-1})**	**AUG**	-15.39	-17.74	-17.19	-25.07	-32.25	-39.24
		SEP	-17.03	-19.03	-18.73	-31.90	-39.46	-47.14
		OCT	-18.17	-19.36	-19.36	-29.52	-32.40	-39.67
		NOV	-7.92	-9.77	-13.30	-17.48	-20.89	-25.34

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	2.60	3.52	-0.56	4.29	2.65	5.79
		Mean	-7.09	-7.76	-9.52	-11.52	-15.22	-17.52
	DOC concentration (mg L^{-1})	**JAN**	-1.10	-0.10	1.20	7.67	11.23	15.50
		FEB	-7.30	-7.73	-6.25	-2.94	-0.46	1.03
		MAR	-10.79	-11.59	-10.20	-8.23	-7.50	-6.49
		APR	-16.64	-16.98	-13.08	-13.81	-14.96	-12.45
		MAY	-8.81	-8.85	-7.59	-5.90	-6.83	-5.64
		JUN	-6.33	-6.39	-5.42	-3.25	-5.14	-4.59
		JUL	0.29	0.21	1.87	3.78	3.85	3.91
		AUG	0.71	-0.37	-0.21	0.67	-1.11	-2.46
		SEP	3.09	2.28	3.89	5.60	7.99	9.38
		OCT	11.09	11.58	12.20	20.52	27.94	33.13
		NOV	17.58	18.26	17.99	31.50	39.44	49.83
		DEC	13.32	14.67	15.96	29.37	37.51	47.77
		Mean	0.95	0.95	2.12	6.98	9.45	12.69
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	-7.10	-3.84	-5.43	6.34	3.73	10.26
		FEB	-1.22	-1.01	0.26	6.20	9.28	10.77
		MAR	-14.85	-17.78	-18.64	-19.08	-18.09	-18.89
		APR	-23.62	-25.83	-22.94	-27.55	-30.67	-31.71
		MAY	-18.45	-20.20	-18.63	-22.61	-28.80	-31.95
		JUN	-21.58	-22.82	-23.73	-25.42	-33.83	-37.60
		JUL	-16.42	-18.08	-16.92	-22.34	-30.49	-37.95
Wye catchment	**DOC flux (g of OC m^{-2} month^{-1})**	**AUG**	-14.79	-18.04	-17.36	-24.57	-33.00	-40.74
		SEP	-14.47	-17.19	-15.57	-28.09	-34.62	-42.18
		OCT	-9.10	-10.03	-9.52	-15.06	-13.51	-19.67
		NOV	8.27	6.71	2.30	8.52	10.32	11.86

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	16.27	18.71	15.32	34.93	41.16	56.33
		Total	-5.65	-6.22	-7.11	-4.10	-5.32	-4.43
Ribble catchment	**Discharge ($m^3 s^{-1}$)**	**JAN**	-3.02	-0.66	-2.54	0.38	-3.70	-0.37
		FEB	1.79	2.10	2.67	7.51	11.21	13.52
		MAR	1.61	-1.55	-4.13	-5.06	-4.06	-5.33
		APR	-5.77	-7.82	-6.61	-10.44	-12.99	-15.63
		MAY	-13.22	-14.62	-14.14	-20.61	-26.80	-30.98
		JUN	-18.63	-19.68	-21.57	-26.48	-34.12	-39.40
		JUL	-18.02	-19.74	-18.50	-27.43	-34.63	-42.95
		AUG	-23.27	-26.74	-25.80	-35.28	-43.89	-50.84
		SEP	-17.76	-15.65	-18.05	-31.53	-37.44	-43.89
		OCT	-11.25	-11.09	-11.70	-20.64	-19.75	-25.82
		NOV	-2.17	-3.39	-6.48	-6.68	-7.92	-9.28
		DEC	5.66	5.37	4.25	10.24	9.47	19.55
		Mean	-6.00	-6.47	-7.47	-9.37	-11.88	-12.42
	DOC concentration ($mg L^{-1}$)	**JAN**	18.85	19.39	20.12	28.99	34.85	40.51
		FEB	16.52	16.80	17.45	26.80	31.69	36.44
		MAR	13.94	13.92	14.02	21.07	24.28	27.57
		APR	10.48	10.53	11.90	17.23	19.49	22.34
		MAY	11.56	11.57	12.27	18.12	19.38	22.69
Ribble catchment	**DOC concentration ($mg L^{-1}$)**	**JUN**	11.58	11.59	10.79	17.69	16.50	16.15
		JUL	10.81	10.72	11.35	14.82	16.66	15.03
		AUG	9.50	7.61	7.92	10.28	7.76	5.48
		SEP	15.53	16.90	16.40	22.12	26.41	29.22
		OCT	14.94	14.84	15.65	23.26	30.42	34.19
		NOV	16.63	16.94	17.58	26.30	31.27	37.26

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	17.23	17.91	18.98	27.56	33.41	36.97
		Mean	13.71	13.73	14.17	20.49	23.43	25.73
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	15.26	18.61	17.07	29.49	29.86	39.99
		FEB	18.61	19.25	20.59	36.32	46.46	54.88
		MAR	15.77	12.15	9.31	14.95	19.24	20.76
		APR	4.10	1.88	4.50	4.99	3.97	3.21
		MAY	-3.19	-4.74	-3.60	-6.23	-12.61	-15.32
		JUN	-9.20	-10.37	-13.11	-13.47	-23.25	-29.62
		JUL	-9.15	-11.13	-9.26	-16.68	-23.73	-34.38
		AUG	-15.98	-21.17	-19.93	-28.63	-39.53	-48.15
		SEP	-4.99	-1.39	-4.61	-16.39	-20.92	-27.49
		OCT	2.01	2.11	2.11	-2.18	4.66	-0.46
		NOV	14.10	12.98	9.97	17.86	20.88	24.52
		DEC	23.86	24.25	24.04	40.62	46.04	63.75
		Total	6.05	5.67	5.00	7.95	7.96	9.31
Derwent (Cumbria) catchment	**Discharge (m^{3} s^{-1})**	**JAN**	5.05	7.80	6.44	17.18	17.02	24.31
		FEB	5.65	6.05	6.54	13.69	17.31	20.65
		MAR	3.11	3.01	2.00	4.42	7.70	8.83
		APR	-1.22	-2.22	-1.07	-2.43	-3.70	-5.61
		MAY	-10.73	-11.95	-10.78	-17.33	-23.52	-28.44
		JUN	-19.44	-20.43	-21.84	-27.31	-35.08	-39.71
Derwent (Cumbria) catchment	**Discharge (m^{3} s^{-1})**	**JUL**	-21.30	-23.74	-21.49	-34.54	-41.41	-48.61
		AUG	-25.08	-28.57	-26.94	-28.93	-49.15	-55.59
		SEP	-22.35	-21.69	-23.15	-32.70	-42.70	-49.13
		OCT	-13.86	-12.34	-13.09	-23.23	-21.99	-28.87
		NOV	4.00	3.36	0.78	1.21	1.87	1.65

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	10.59	13.01	12.01	21.29	22.42	36.65
		Mean	-3.20	-2.90	-3.45	-2.76	-4.85	-3.75
	DOC concentration (mg L^{-1})	**JAN**	2.73	2.88	2.50	1.58	4.98	5.37
		FEB	1.73	2.09	1.24	0.65	3.54	4.11
		MAR	1.34	1.69	0.57	-0.13	2.87	3.10
		APR	1.22	1.49	0.57	-1.30	2.02	3.53
		MAY	3.64	3.47	3.32	0.96	5.58	8.51
		JUN	4.70	4.51	3.76	1.99	7.44	9.31
		JUL	7.07	7.92	6.88	4.58	12.93	14.54
		AUG	11.08	10.73	10.18	9.78	19.52	24.08
		SEP	10.68	10.31	10.58	9.56	21.88	27.21
		OCT	14.06	13.56	14.64	15.83	29.25	36.72
		NOV	10.92	10.86	12.05	13.84	23.23	29.38
		DEC	5.82	5.70	6.11	6.09	11.86	13.66
		Mean	7.29	7.26	7.12	6.49	14.20	17.56
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	7.92	10.91	9.10	19.03	22.85	30.98
		FEB	7.48	8.26	7.87	14.43	21.47	25.61
		MAR	4.49	4.75	2.59	4.28	10.79	12.20
		APR	-0.02	-0.76	-0.51	-3.70	-1.75	-2.28
		MAY	-7.49	-8.89	-7.82	-16.54	-19.25	-22.35
		JUN	-15.65	-16.84	-18.90	-25.86	-30.25	-34.09
		JUL	-15.74	-17.69	-16.08	-31.54	-33.83	-41.14
Derwent (Cumbria) catchment	**DOC flux (g of OC m^{-2} month^{-1})**	**AUG**	-16.78	-20.90	-19.51	-21.98	-39.23	-44.90
		SEP	-14.06	-13.62	-15.02	-26.26	-30.17	-35.29
		OCT	-1.75	-0.45	-0.37	-11.08	0.82	-2.76
		NOV	15.36	14.59	12.92	15.22	25.52	31.51

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	17.03	19.45	18.85	28.68	36.94	55.32
		Total	1.53	1.68	1.12	0.21	3.37	5.96
Eamont catchment	Discharge ($m^3 s^{-1}$)	JAN	4.66	7.67	6.27	13.83	12.82	17.97
		FEB	5.29	5.93	6.32	9.89	12.84	14.63
		MAR	-4.89	-4.98	-6.22	-8.13	-7.00	-8.31
		APR	-14.49	-15.39	-15.05	-20.00	-22.08	-25.47
		MAY	-33.77	-34.75	-33.95	-40.22	-45.23	-49.03
		JUN	-34.29	-35.05	-36.38	-41.37	-47.42	-51.25
		JUL	-37.79	-39.60	-37.88	-47.01	-51.86	-57.29
		AUG	-42.38	-44.87	-43.58	-51.89	-57.10	-61.53
		SEP	-44.15	-43.83	-44.57	-51.25	-54.65	-58.15
		OCT	-42.92	-41.74	-42.46	-49.75	-48.67	-53.60
		NOV	-15.34	-15.74	-18.20	-19.38	-20.20	-22.53
		DEC	1.18	3.37	2.11	7.96	7.61	18.54
		Mean	-16.44	-16.03	-16.70	-17.75	-19.16	-18.96
		JAN	3.03	2.65	3.02	2.13	1.77	0.38
	DOC concentration ($mg L^{-1}$)	FEB	0.64	0.76	0.92	-0.01	-1.03	-2.24
		MAR	-0.10	-0.02	-0.06	-0.34	-1.85	-3.36
		APR	0.15	0.45	0.54	0.11	-0.49	-2.48
		MAY	3.33	3.91	3.92	7.73	6.27	5.20
		JUN	6.11	7.17	6.08	8.07	10.58	9.79
		JUL	10.52	8.97	8.97	14.57	12.33	20.22
	DOC concentration ($mg L^{-1}$)	AUG	12.29	13.59	12.49	15.27	17.75	18.63
		SEP	12.20	11.23	11.28	16.45	22.00	24.78
		OCT	17.42	17.09	19.01	24.35	31.03	36.51
		NOV	13.13	13.19	14.19	17.47	19.44	22.90

Catchment	Items	Month	2030s B1 change (%)	2030s A1B change (%)	2030s A1F1 change (%)	2090s B1 change (%)	2090s A1B change (%)	2090s A1F1 change (%)
		DEC	7.54	7.57	8.03	8.05	8.84	8.01
		Mean	8.10	8.09	8.24	10.76	12.13	13.56
	DOC flux (g of OC m^{-2} month^{-1})	**JAN**	7.83	10.53	9.49	16.25	14.82	18.41
		FEB	5.97	6.73	7.30	9.87	11.67	12.06
		MAR	-4.99	-4.99	-6.28	-8.45	-8.72	-11.39
		APR	-14.36	-15.01	-14.59	-19.92	-22.46	-27.33
		MAY	-31.57	-32.20	-31.36	-35.60	-41.80	-46.38
		JUN	-30.27	-30.40	-32.52	-36.64	-41.86	-46.48
		JUL	-31.25	-34.18	-32.31	-39.29	-45.93	-48.66
		AUG	-35.30	-37.38	-36.54	-44.55	-49.48	-54.36
		SEP	-37.34	-37.52	-38.31	-43.23	-44.68	-47.77
		OCT	-32.97	-31.78	-31.52	-37.51	-32.74	-36.66
		NOV	-4.22	-4.63	-6.59	-5.29	-4.69	-4.80
		DEC	8.80	11.20	10.31	16.65	17.12	28.03
		Total	-13.64	-13.39	-13.78	-14.81	-16.02	-16.31

Appendix G
Supplementary figures for Chapter 4 (Paper III)

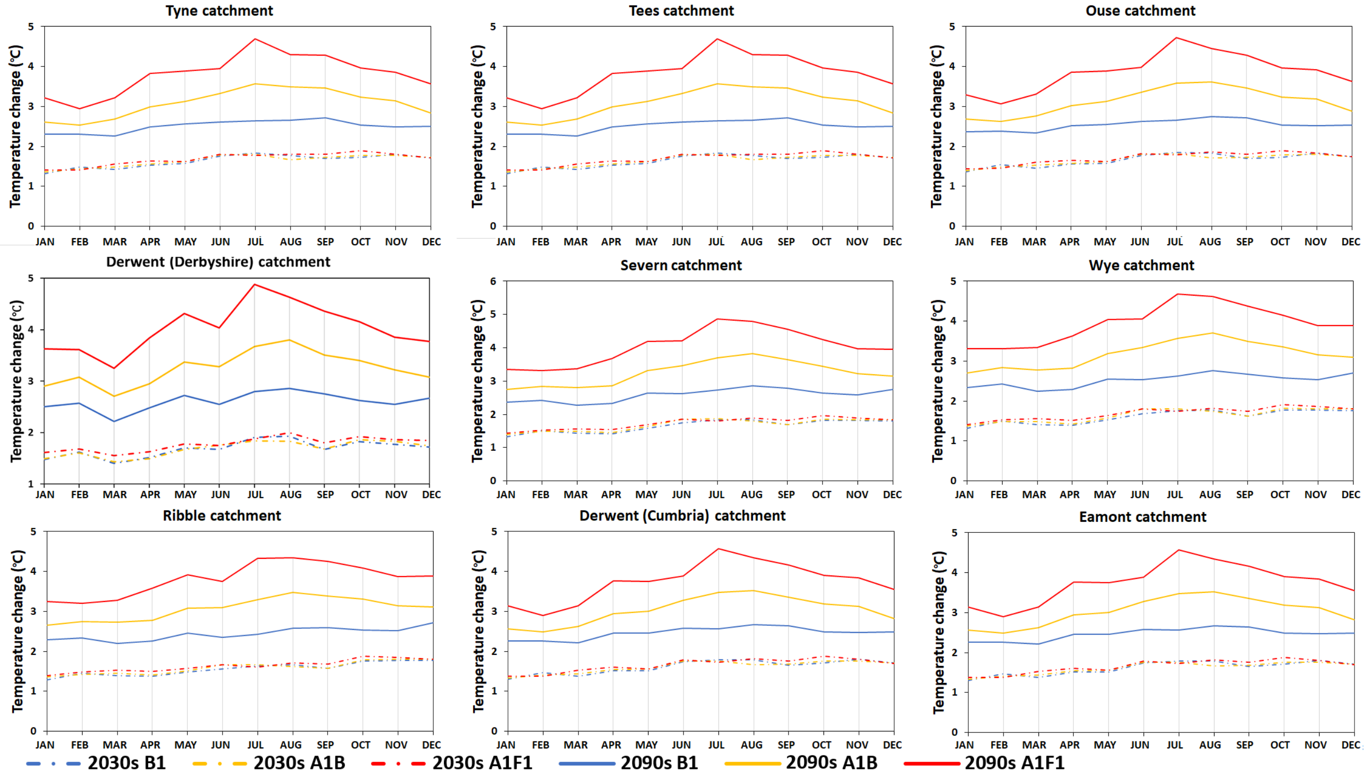

Figure G.1 Changes in average monthly temperature under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades 2030s and 2090s compared with during the observational baseline period.

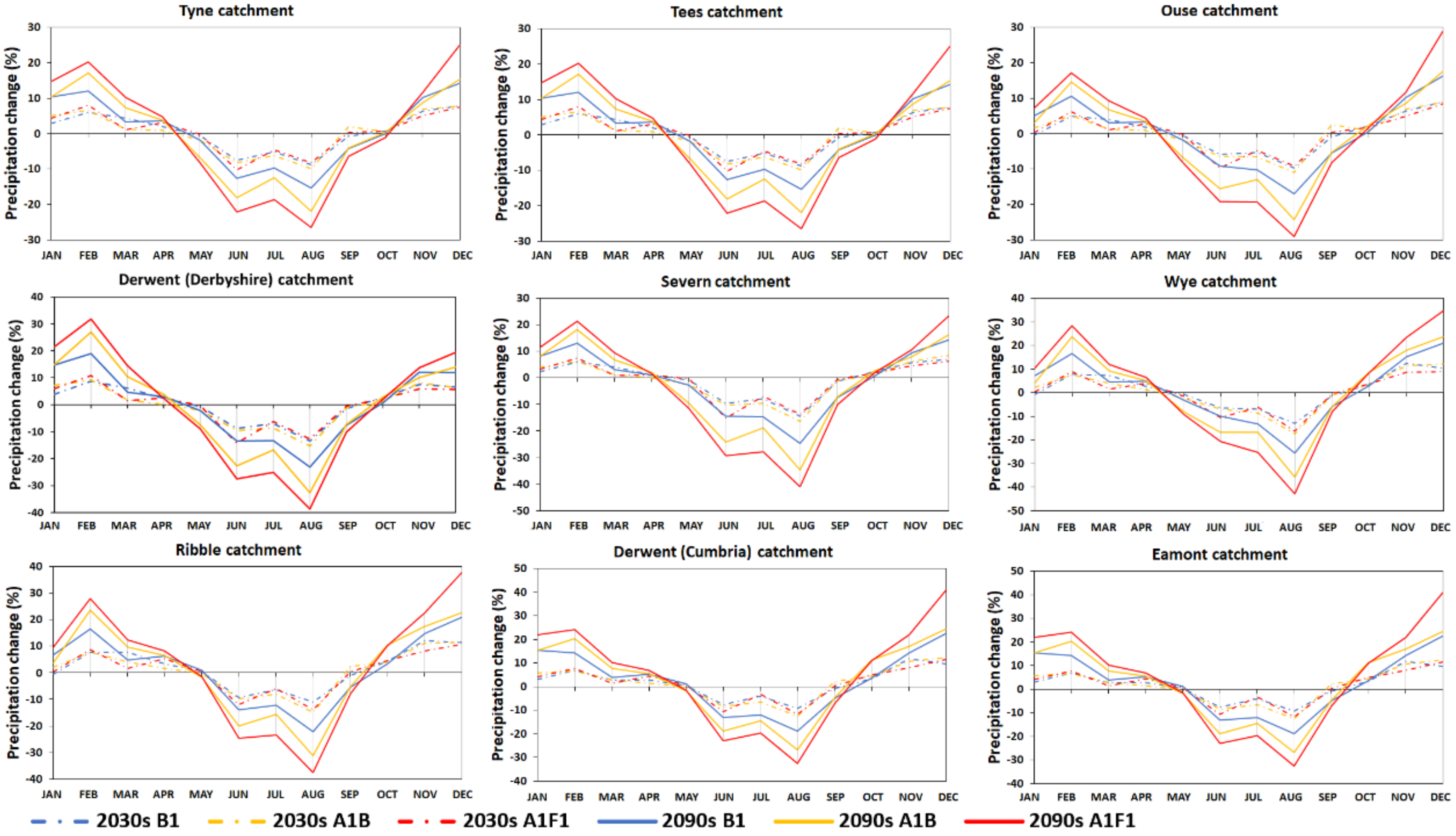

Figure G.2 Changes in average monthly precipitation under UKCP09 B1 (lowest emissions), A1B (medium emissions), and A1F1 (highest emissions) SRES scenarios for the decades 2030s and 2090s compared with during the observational baseline period.