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A GIS based MCE model for identifying water colour generation potential in UK upland drinking water supply catchments

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SUMMARY

Water discolouration is one of the key water quality problems faced by UK water companies taking raw water from peatland catchments. A water colour model has been developed using a combined Geographical Information System and Multicriteria Evaluation approach. The model was used to predict water colour production potential based on key land management practices controlling colour production in UK upland catchments. Calibration of the model with historic data collected at water treatment works treating water from upland areas showed that the model was potentially capable of accurately predicting water colour production potential at the catchment scale (c. 90%). Subsequent validation has shown this to be the case. Rotational heather burning and vegetation type (particularly heather) were identified as the two most statistically significant variables influencing water colour generation in the study catchments. It was predicted that colour is generated in particular hotspots and management to improve water quality should, therefore, focus on such areas. Blending of water is also an important process in controlling colour at the catchment scale and at water treatment works, with high colour often being diluted by runoff from land elsewhere in the catchment with lower potential to generate colour.

1. Introduction

Peat bogs represent the single largest terrestrial carbon reserve within the UK, currently acting as a net sink of carbon (Cannell et al., 1993). Over recent decades Dissolved Organic Carbon (DOC) losses from upland peat catchments have increased however (Evans et al., 2005, 2006; Worrall et al., 2003, 2004; Worrall and Burt, 2007a). Were these losses to continue then UK upland peats may switch to become a net source of carbon (Worrall et al., 2006). Losses of DOC from upland peat concern not only the scientific community but also the UK water industry as upland catchments contribute >70% of all drinking water (Watts et al., 2001). DOC and water colour have been found to be highly correlated as it is the presence of this DOC that results in water becoming coloured (Worrall et al., 2003), although not all DOC results in the colouration of water. During treatment DOC can interact with chlorine to produce carcinogenic compounds, including Trihalomethanes (THMs), Haloacetic Acids (HAAs) and other halogenated compounds (Fearing et al., 2004).

Within the UK, long-term DOC records from upland catchments are limited in number (Evans et al., 2005; Worrall et al., 2003, 2008) and their spatial coverage tends to be small. Indeed, while the UK Acid Waters Monitoring Network (AWMN) has measured DOC at 22 UK sites since 1988 the majority are located within Scotland and Wales, with only 5 sites located in England, of which two are lakes and only one riverine site is in northern England (Monteith and Evans, 2005).

The UK water industry routinely measures water colour at Water Treatment Works (WTWs) to ensure compliance with EU drinking water regulation (EC, 1998). Due to the strong relationship between DOC and colour (Worrall et al., 2005) it is possible to use the available long-term water colour records as proxies to establish long-term trends in DOC. These records, therefore, provide a valuable insight into long term trends in DOC/colour release from UK upland peat catchments and offer an opportunity to compare catchments to identify key drivers, particularly the impacts of land management and reasons for inter-catchment variability.

Estimates suggest that for England and Wales treatment for soil erosion and organic carbon losses are currently >£106 m per annum (Pretty et al., 2000) catchment management offers the potential to reduce these 'end of pipe' treatment costs by treating the problem 'at source'. DOC losses and colour production exhibit considerable spatial variability both between and within catchments, with small areas typically generating extreme discolouration (Butcher et al., 1992). Therefore, the identification of critical land management practices and 'hot spots' would aid catchment management strategies.

Bacterial breakdown of terrestrial organic matter is the major source of DOC observed in stream waters, with humic and fulvic

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acids accounting for the bulk of these (50–75%) (Thurman, 1985). Despite significant increases in DOC losses being observed over the past few decades (Evans et al., 2005, 2006; Freeman et al., 2001a; Worrall and Burt, 2004; Worrall et al., 2003; Worrall and Burt, 2007b) the mechanisms driving these are not fully understood. Worrall et al. (2007a) summarised the various drivers believed to have an influence on increased DOC losses observed within the UK, these include: increased air temperature (Freeman et al., 2001a); land management (Worrall et al., 2003); changes in the amount and nature of flow (Tranvik and Jansson, 2002); eutrophication (Harriman et al., 1998); severe summer drought (Freeman et al., 2001b; Worrall et al., 2004); and decreasing acid deposition (Clark et al., 2005; Evans et al., 2006; Monteith et al., 2007). Despite this there is little consensus as to the major driver of these increases.

Land management practices have significantly impacted the UK uplands. Rotational burning is the most widely applied upland management technique, with burning intensity having increased significantly over the past few decades (Yallop et al., 2005, 2006). Evidence indicates that burning influences the production of DOC and colour, however, debate exists as to whether burning increases (Miller, 2008; Mitchell and McDonald, 1992; White et al., 2007) or decreases (Worrall et al., 2007a, b) colour production. Within the Yorkshire region of the UK the proportion of new burn on deep peat (Winter Hill series) has been suggested as the single largest predictor of water discolouration (White et al., 2007; Yallop and Clutterbuck, 2009).

Furthermore, throughout the 1960s and 1970s large scale drainage (gripping) of UK upland peats occurred (Holden et al., 2004). This process stimulates DOC production by increasing the volume of peat exposed to bacterial activity and oxidation (Mitchell and McDonald, 1992; Worrall and Burt, 2005). Significantly increased DOC and colour in soil water solutions have been observed in artificially drained peat compared with intact peat (Wallage et al., 2006). Although gully and grip blocking are the main scientifically proven management strategies for reducing water colour (Kay et al., 2009) the impacts of grip blocking vary. Wallage et al. (2006) observed a 60–70% decrease in water colour at blocked sites. In contrast, colour has also been found to increase in blocked drains shortly after blocking occurred (Worrall et al., 2007b), although this may result from the flushing out of DOC already built up in the peat.

Vegetation may play an important control in the production of water colour. Within the UK upland land management has encouraged the growth of *Calluna* (moorland heather) for various agricultural reasons. Evidence suggests that *Calluna* can suppress the water table through evapotranspiration, therefore increasing colour production (Clutterbuck and Yallop, 2010), with land under mature heather accumulating DOC through the summer (White et al., 2007). The presence of *Calluna* can also promote the production of peat pipes (Holden, 2005) which will affect hydrological pathways in areas of peat dominated by *Calluna*. Miller (2008) observed elevated water colour loss from dried and re-wetted peat under heather compared to grass. Indeed, heather dominated gripped catchments produced the highest water colour followed by mixed vegetation and grass dominated catchments in a recent UK-wide study (Armstrong et al., 2007, 2010).

Other variables found to influence colour production at the local scale include soil type (Hope et al., 1997; Tipping et al., 1999), slope angle and aspect (Mitchell and McDonald, 1995; Mitchell, 1991), precipitation amount and intensity (Scott et al., 1998) and afforestation (Baker et al., 2008; Watts et al., 2001).

2. Modelling

While attention has focussed on the mechanisms driving increases in DOC and on measuring DOC release, modelling DOC/colour release in upland catchments has received little attention. Modelling offers considerable potential to not only predict DOC and water colour concentrations at a range of scales but also offers the opportunity to identify problem areas and as a result of this those variables responsible for driving high DOC concentrations and water colour.

As there is still considerable debate as to which processes drive the production of water colour and DOC in upland catchments the development of a process driven numerical model to estimate water colour concentrations is far from straightforward and would not be possible with the data available at this time. Instead this research aimed to use current scientific knowledge outlined in the available literature along with long term records of water colour (and by proxy DOC) to:

1. Develop a model capable of predicting colour concentrations at the catchment scale.
2. Use the model inversely to further investigate drivers of water colour production and identify those key factors capable of accounting for differences between catchments.
3. Subsequently, validate the model in an additional upland water supply catchment where historic water colour data are available.

The model output will then help inform future catchment management decisions aimed at reducing water colour.

3. Methods

3.1. Site selection

The majority of the c. 120 reservoirs used in the supply of drinking water in Yorkshire are located along the eastern edge of the Pennines (Southern Pennines and Peak District). Water colour is routinely measured across the network of WTWs within Yorkshire, with concentrations given as mg l^{-1} Pt Co (Hazen, 1892; ISO2211, 1973). Colour in drinking water must not exceed 20 mg l^{-1} (EC, 1998; Hongve and Akesson, 1996; Hongve et al., 2004) and where 60 mg l^{-1} is exceeded the capacity to remove colour is diminished (Pattinson et al., 1995). More typically, colour may also be measured using light absorbance at specific wavelengths with 254 and 400 nm being typical values (Armstrong et al., 2010; Clay et al., 2009). Within Yorkshire many of the WTWs taking water from upland catchments have experienced increases in water colour since the mid 1990s (Yorkshire Water, unpublished data). An extensive search of water colour records from WTWs across Yorkshire identified 18 sites suitable for inclusion in this study to test and calibrate the water colour model; 12 with historic (post 1995) mean colour >60 mg l^{-1} Pt Co and 6 < 60 mg l^{-1} Pt Co (Fig. 1). In order to be used in the study, the WTW colour data had to relate to a known catchment and not receive raw water from multiple sources (e.g. major river intakes piped to the WTW in addition to runoff from its natural catchment area) which changed periodically. The data record also had to be of good temporal resolution (typically weekly data from 1995 to 2006, although in many cases sampling was more frequent, i.e. daily). All of the monitoring data therefore either relates to a catchment with an individual reservoir or several (<6) nested reservoirs.

3.2. Model development

Multi-criteria evaluation (MCE), including multiattribute decision making (MADM), is a powerful tool for interrogating complex datasets (Malczewski, 1999). Of the various spatial MADM approaches simple additive weighting (SAW) is the most common and when this is combined with GIS it is possible to use the technique to compare datasets from spatially discrete areas. This