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High-resolution wetness index mapping: a useful tool for regional scale wetland management

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ABSTRACT

Wetland ecosystems are key habitats for carbon sequestration, biodiversity and ecosystem services, yet in many they localities have been subject to modification or damage. In recent years, there has been increasing focus on effective management and, where possible, restoration of wetlands. Whilst this is highly laudable, practical implementation is limited by the high costs and unpredictable rates of success. Accordingly, there is a need for spatial information to guide restoration, ideally at the regional scale that land managers operate. In this study, we use high-resolution Light Detection and Ranging (LiDAR)-derived elevation, in conjunction with regional soil and land cover maps, to model the wetness potential of an area of conservation importance in north-west England. We use the Compound Topographic Index (CTI) as a measure for the site-specific wetness and potential to be receptive to wetland restoration. The resulting model is in agreement with the regional-scale distribution of wetlands and is clearly influenced by the topographic and soil parameters. An assessment of three representative case studies highlights the small scale features that determine the potential wetness of an area. For each site, the model results conform to the expected patterns of wetness, highlighting restoration and management activity. Furthermore, areas showing high potential wetness that may be suitable for wetland habitat creation, are highlighted. The increasing availability of LiDAR data at regional and national scales will allow studies of this nature to be undertaken at previously unobtainable resolutions. Simple models, such as implemented here, benefit from explainability and relatability and have clear potential for use by managers and conservation agencies involved in wetland restoration.

Keywords: Wetlands, Spatial modelling, LiDAR, Compound Topographic Index, Restoration

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1 Introduction

Wetlands are among the most biodiverse and carbon-rich habitats in the northern hemisphere and provide vital ecosystem services, such as flood prevention and water purification (Euliss-Jr. et al. 2006; Ostle et al. 2009). They are also one the most altered ecosystems, with a long history of manipulation and development (Holden, Chapman, and Labadz 2004). In Britain, artificial draining of wetlands has occurred since pre-Roman times, with accelerated rates since the Industrial Revolution in the early 1800s (Darby 1956; Holden, Chapman, and Labadz 2004). Common drivers for this habitat loss include drainage for agricultural expansion, drying due to conifer forestry, extraction for fuel or fertiliser, and water table manipulation for attempted flooding control (Lindsay, Birnie, and Clough 2014; Robinson and Armstrong 1988). Peatlands and lowland raised bogs, in particular, have suffered large losses, with only 338 ha of active, undamaged, peat-forming bog remaining in England from a total of ~36,000 ha (JNCC 2011).

More recently, an increased appreciation of the ecological, hydrological and climate regulating services provided by wetlands has reshaped management priorities and provided a renewed focus on the maintenance and restoration of wetlands. However, restoration work is expensive and success unpredictable, therefore improved data on the potential of sites to be receptive of restoration efforts is pressing (Bateman et al. 2013; Mitsch and Cronk 1992).

On a regional scale, wetland distribution is determined by the inflow and retention of water which in turn, is generally governed by topography (Beven 1997; Beven and Kirkby 1979). Beven and Kirkby (1979) first proposed that site-specific moisture conditions could be modelled as a function of upstream area and slope steepness; this Compound Topographic Index (CTI) has proved an effective metric for a range of geomorphic, ecological, and hydrological purposes. The CTI, and it's modifications, have been used to map the current and potential wetness for a range of locations and environments including: continental Europe (riparian woodlands and grasslands, mires; Merot et al. 2003), northern Sweden (mires; Rodhe and Seibert 1999), and the eastern United States (wet woodlands; Lang et al. 2013)

Over the last decades, topographic modelling has been aided by the free availability of global coverage Digital Elevation Models (DEMs), products such as the USGS GTOPO30 ($\sim$1 km resolution), NASA STRM ($\sim$30 and $\sim$90 m resolution), and NASA/JAXA ASTER DEM (30 m), all of which allow regional analyses at minimal expense and computation. However, these resolutions are more suited for hydrological applications focusing on general patterns of water movement (Beven 1997). For ecological studies, finer scale data sources are needed to discriminate small-scale features (Rodhe and Seibert 1999; Sørensen and Seibert 2007).

In recent years, the advent of Light Detection And Ranging (LiDAR) technology has greatly increased the availability of high-resolution (< 10 m) elevation data. This has facilitated a shift in focus towards small scale, site-specific hydrology and the resulting vegetation (Moeslund et al. 2013).The high cost of LiDAR data has historically limited this resource to small areas (e.g. Lane et al. 2003; Maxa and Bolstad 2009). However, national-scale acquisition plans combined with open data policies for a number of countries now enables large-scale monitoring at previously unobtainable resolutions. In England, the Environment Agency recently made 0.25 - 2 m resolution DEMs derived from LiDAR freely available, offering a valuable resource for hydrological modelling.

In this study, we use high-resolution (4 m) LiDAR-derived elevation data to map potential wetland habitats across the wider Greater Manchester region, Northwest England. This is the first high-resolution regional-scale effort to map wetland potential. Our main objectives are: 1) to identify areas of potential wetland habitats in the Greater Manchester region, 2) test the modelled outputs at smaller site-scales, and 3) explore the strengths and limitations of high-resolution CTI maps. Results from this study will aid local conservation organisations in making informed decisions on the continued management and potential restoration of the region's wetlands.

2 Materials and Methods

2.1 Study Area

Our study area is located in Northwest England, ranging from the Mersey basin in the south to the West Pennine Moors in the north (Figure 1). This region has a mild oceanic temperate climate (Köppen-Geiger classification: Cfb, (Kottek et al. 2006) with mean annual rainfall of 867 mm/year and a mean monthly maximum temperature of 13.2 °C. The climate is broadly constant across the study area, with a slight west-east increase in rainfall (Met Office 2016). Topographically, the area varies from the undulating West Pennine Moors in the north-east (up to 456 m asl), to the relatively flat plains bordering the Mersey basin in the south (around 10 m asl).

The area encompasses around 48,000 ha of varied wetland habitats from open water, fen, reed beds, and marshes to blanket and lowland raised bogs, many of which have been subjected to development or modification in the past 100 years. The area is a designated Local Nature Improvement Area (NIA) and managed under the Great Manchester Wetlands Partnership. The ecological goal of this partnership is to restore wetland habitats and habitat connectivity to support species movements across the area and increase carbon sequestration and storage. These opportunities exist across a variety of sites from ex-brownfield areas, including coal measures, agricultural grasslands and cutover peatlands.

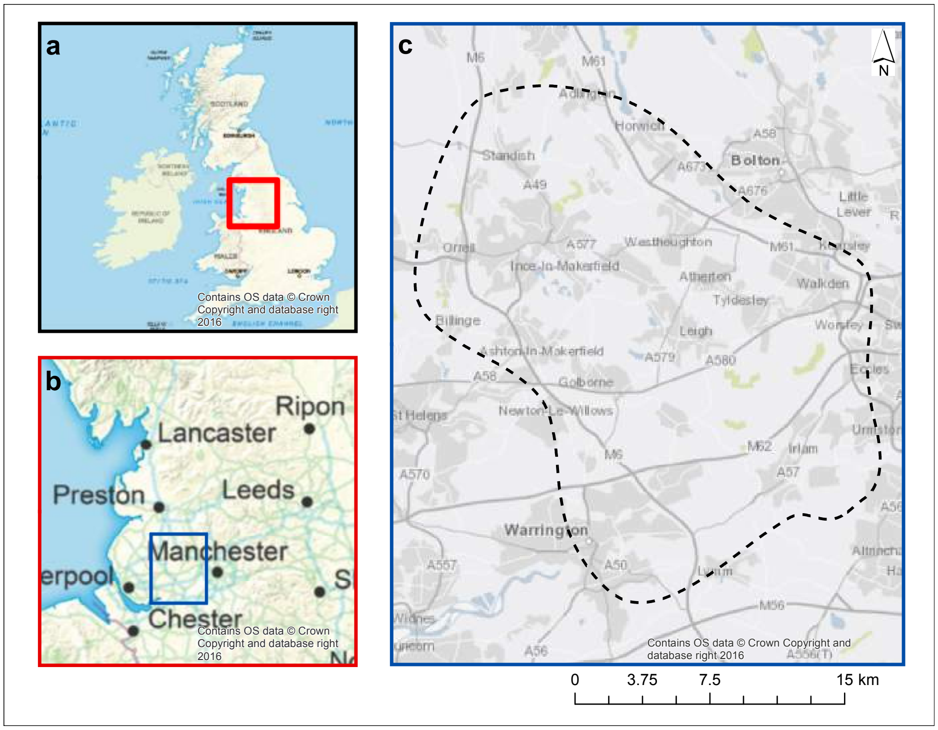

Figure 1. Study area in a) the UK, b) Northwest England, and c) The wider Great Manchester area, the dashed line delineates the Nature Improvement Area for the Great Manchester Wetlands

2.2 Data

2.2.1 Digital Elevation Model

In England, the Environment Agency provides high-resolution LiDAR- derived Digital Terrain Models (DTMs) covering roughly 75% of the country. These DTMs are produced from aerial LiDAR surveys, with final products composited from surveys undertaken between 1998 and 2015, with the most recent observations taking precedence. The error range for the composited layers is ± 40 cm in the planar (xy) dimension, and ± 15 cm (root-mean-square error) or ± 5 cm (random) for the vertical (z) dimension. Different survey flights were combined by applying a 30 m feathering overlap to ensure a seamless integration. In this study, we used the 2 m resolution composited DTM product, aggregated to 4 m to reduce computation time.

2.2.2 Soils

Soil data were obtained from the National Soil Resources Institutes's Soil Map (NSM) (Mayr and Palmer 2006). This database groups soils into 27 units, at a 1:50,000 scale. Each unit possesses an accompanying drainage classification (low-high), determined through analysis of field surveys and historical data. These classifications were aggregated into six new categories, based on their drainage characteristics (Table 1).

2.2.3 Land Cover

Land cover data were extracted from the National Land Cover 2007 (LCM2007) product, produced by the Centre for Ecology and Hydrology. This is a 25 m resolution map featuring 23 land cover types for the United Kingdom (Morton et al. 2011). Produced from an amalgamation of Landsat, SPOT, IRS-LISS3, and AWIFS satellite imagery, combined with extensive ground reference survey data, the LCM-2007 data are consistent with national cartographic boundaries (Morton et al. 2011). Land cover types were aggregated into four classes (very high, moderate, low, very low) based on their drainage potential (Table 1). These classes were determined based on the generalised ability of the land to withhold water: with 'very high' indicating complete impermeability, whilst 'very low' classes have continual standing water. To enable the transferability of methods, groupings were kept broad.

2.2.4 Priority Habitat Inventory

The locations of known verifiable wetland habitats were acquired from the Priority Habitat Inventory (PHI), maintained by Natural England (Natural England 2016). This is a spatial database for habitats of conservation importance within England, locations are maunally surveyed by regional specialists based on Biodiversity Action Plan (BAP) requirements. We selected all records corresponding to wetland environments resulting in nine classes. Whilst not encompassing all known wetland sites, the PHI allows us to undertake a regionally representative validation exercise.

2.3 The Compound Topographic Index

The Compound Topographic Index (CTI), also known to as the Topographic Wetness Index (Hengl, Gruber, and Shrestha 2003) , is a simple hydrological metric for quantifying the steady-state wetness of an area. For a given raster cell i, it is defined as:

$$CTI_i = \ln \frac{\alpha_i}{\tan \beta_i} \tag{1}$$

where α is the up-stream contributing area (m^2 per unit flow width perpendicular to the flow direction) and β is the corresponding slope (radians) (Beven and Kirkby 1979). These components are derived from the DEM, by the process shown in Figure 3. Hydrologically, this formula relates the potential of an area to receive water (α) against potential loss or retention of moisture (β). By dividing the up-steam contributing area, i.e. the up-slope drainage area, by the corresponding slope, CTI values are proportional to the potential wetness and lateral transitivity of a site. The larger the CTI, the greater potential for the landscape to hold water. Although a simplistic metric,

Drainage Potential	Land Cover	Soil
Very High (6)	Inland rock, urban, suburban	Freely draining slightly acid sandy (loamy); Sand dunes
High (5)		Slightly acid loamy and clayey soils with impeded drainage
Moderate (4)	Arable and horticulture, improved/rough/natural/acid grassland	Naturally wet very acid sandy and loamy
Low-Moderate (3)		Slowly permeable seasonally wet acid loamy (base-rich loamy) and clayey
Low (2)	Broadleaved/coniferous woodland, heather/heather grassland	Blanket/raised bog peat soil
Very Low (1)	Fen, marsh, swamp, bog	Very acid loamy upland soils with a wet peaty surface

Table 1. Drainage classification of soil and land cover data. Soil rankings are taken from the National Soil Map database (Mayr and Palmer 2006), land cover types are grouped based on hydrological similarities. Only soil and land covers present in the study area are mentioned

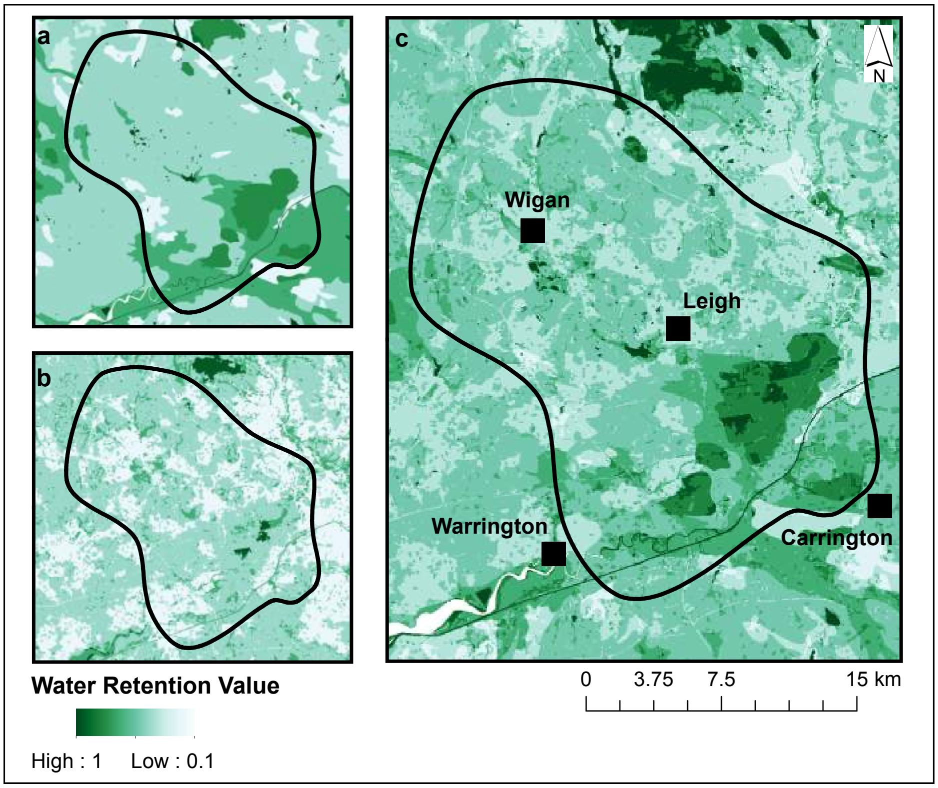

Figure 2. Drainage scores for a) soil, b) land cover, and c) combined soil and land cover

CTI values have been shown to be indicative of soil organic matter, erosion potential, and wetland extent (Beven 1997; McKenzie and Ryan 1999).

We calculated the CTI for the Great Manchester NIA region, using the LiDAR DEM, as detailed in Figure 3. The slope layer is calculated based on the maximum difference between each pixel and the eight neighbours. Flow direction was determined by using a eight direction (D8) model, whereby flow is assumed to follow the steepest decent based on the neighbouring eight cells (Garbrecht and Martz 1997). The number of cells that flow into a pixel is summed to calculate the flow accumulation. This is then converted into the up-stream contributing area by adding 1, to account for the candidate pixel, and multiplying by the DEM cellsize. The up-slope contributing area can weighted to account for varying levels of drainage received from neighbouring pixels. We created an aggregated water retention layer from the land cover and soil datasets (Figure 2), based on a scaled sum of the drainage potential values in Table 1. A high weighting value will simulate the retention of water; for example, due to peaty soil or forest cover. Conversely, low weighting values associated with sandy soils and impervious land cover will encourage the loss of water. Thus accommodating varying overland flow and hydraulic conductivity rates present in a region, providing a more realistic representation. To reduce uncertainty in the weight layer, the individual drainage classes were kept generalised, so that only the main regional patterns were

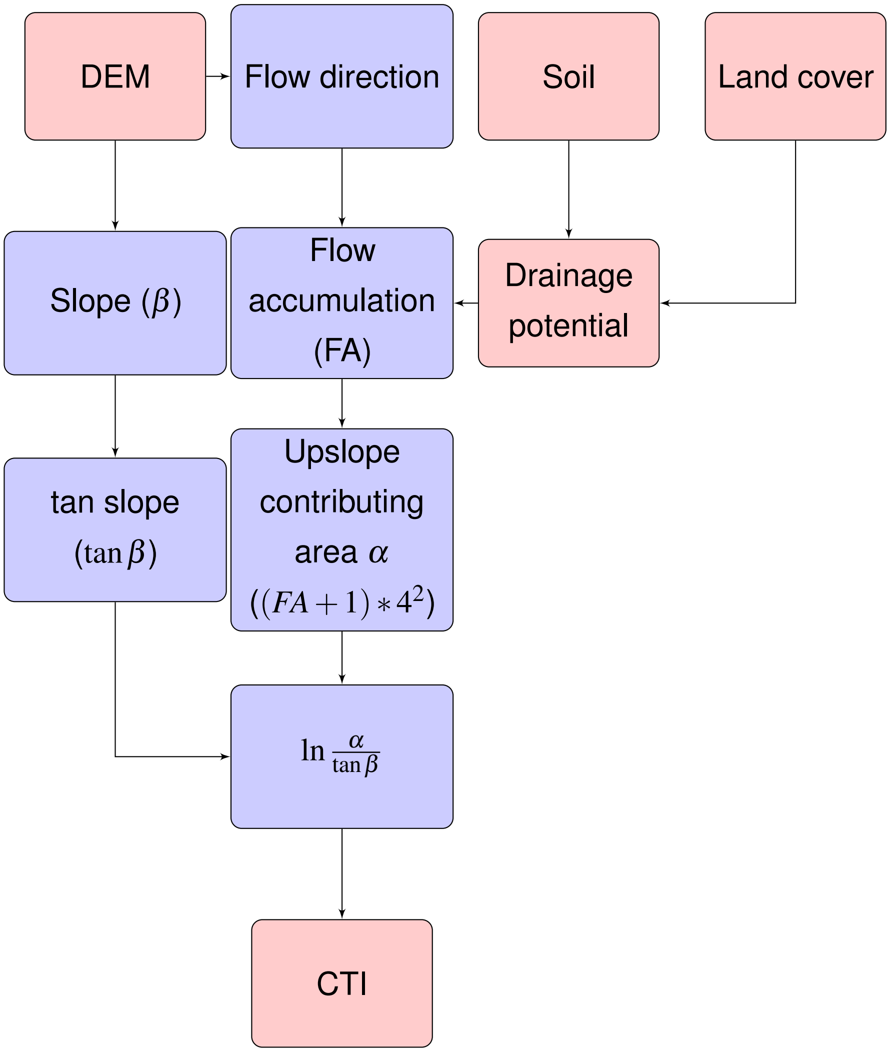

Figure 3. Flowchart of the process for generating the Compound Topographic Index from the DEM

captured.

Processing was undertaken using the free and open source software packages of "TauDEM" (Tarboton 2005) and "raster" (Hijmans 2016) within the R Statistical Computing Environment (R Core Team 2016).

To validate the derived CTI layer, 3000 random points were selected for: i) generic non-wetland areas, and ii) each wetland class from the PHI. Analysis of Variance (ANOVA) was used to test for a significant difference between these groups, with a post-hoc Tukey's Honest Significant Difference (HSD) test used to identify group-level differences.

3 Results and Discussion

3.1 Regional Overview

The Great Manchester wetlands region displays a wide range of wetness potential values, as derived from the CTI output (Figure 4).The CTI scores have a range of 0 to 28, $\bar{x}$ = 8.30 and SD = 2.51. The overall distribution of CTI values reflects the topological variation of the region, with the highest scores (dark blue areas in Figure 4) falling into several categories. High scoring pixels north-west of Carrington (Figures 5a and 5b) are dominated by lowland peats, high values between Wigan and Leigh correspond to subsistence induced lakes and reed beds (Figure 5c), whilst the area west of Bolton is characterised by upland raised peats in the West Pennine Moors. Low scoring areas (light yellow in Figure 4) correspond to urban and built-up areas, with road and rail networks appearing as very low values. These patterns relate to the broad-scale distribution of wetlands in the regions, and highlight the role of auxiliary data in the form of soil and land cover maps to guide the topographic index modelling.

The clear distinction of landscape-scale patterns is reassuring. A number of studies have observed that when using high-resolution DEMs regional patterns are obscured by local micro-topographic variation (Drover et al. 2015; Sørensen and Seibert 2007; Wolock and Price 1994). This is normally attributed to a reduction in the up-slope drainage area as calculated when using smaller pixels (Sørensen and Seibert 2007). The success of our model in this regard could be attributed to a number of factors: our considerably larger study area compared, to previous studies, should increase the up-slope drainage area, reducing the influence of small-scale features. Furthermore, the high accuracy and precision of the LiDAR data should allow flow patterns to navigate potential blockages that would be obscured by coarse DEMs.

The CTI outputs for wetland and non-wetland sites (Figure 6) indicates that the designated areas generally have higher values. This is supported by the ANOVA results which highlighted a significant difference between the groups (F= 268.5, P <0.05). However, not all classes were significantly different from the non-wetland samples (Tukey's HSD >0.05, black squares in Figure 6 indicate significant differences). This can partially be explained by the nature of sites included in the PHI: many blanket bogs are designated to facilitate restoration efforts, and therefore, have low water retention and CTI values. Comparably, mudflats are commonly situated on tidal rivers and estuaries (e.g the Mersey) and have limited topographic-induced wetness.

To provide a site-specific insight on the potential and limitation of CTI outputs for characterising wetlands at a regional scale, we analysed three case study sites that are representative of local wetland habitats and are the focus of on-going conservation and restoration efforts: Carrington Moss, Risley Moss, and the Wigan Flashes (Figure 5).

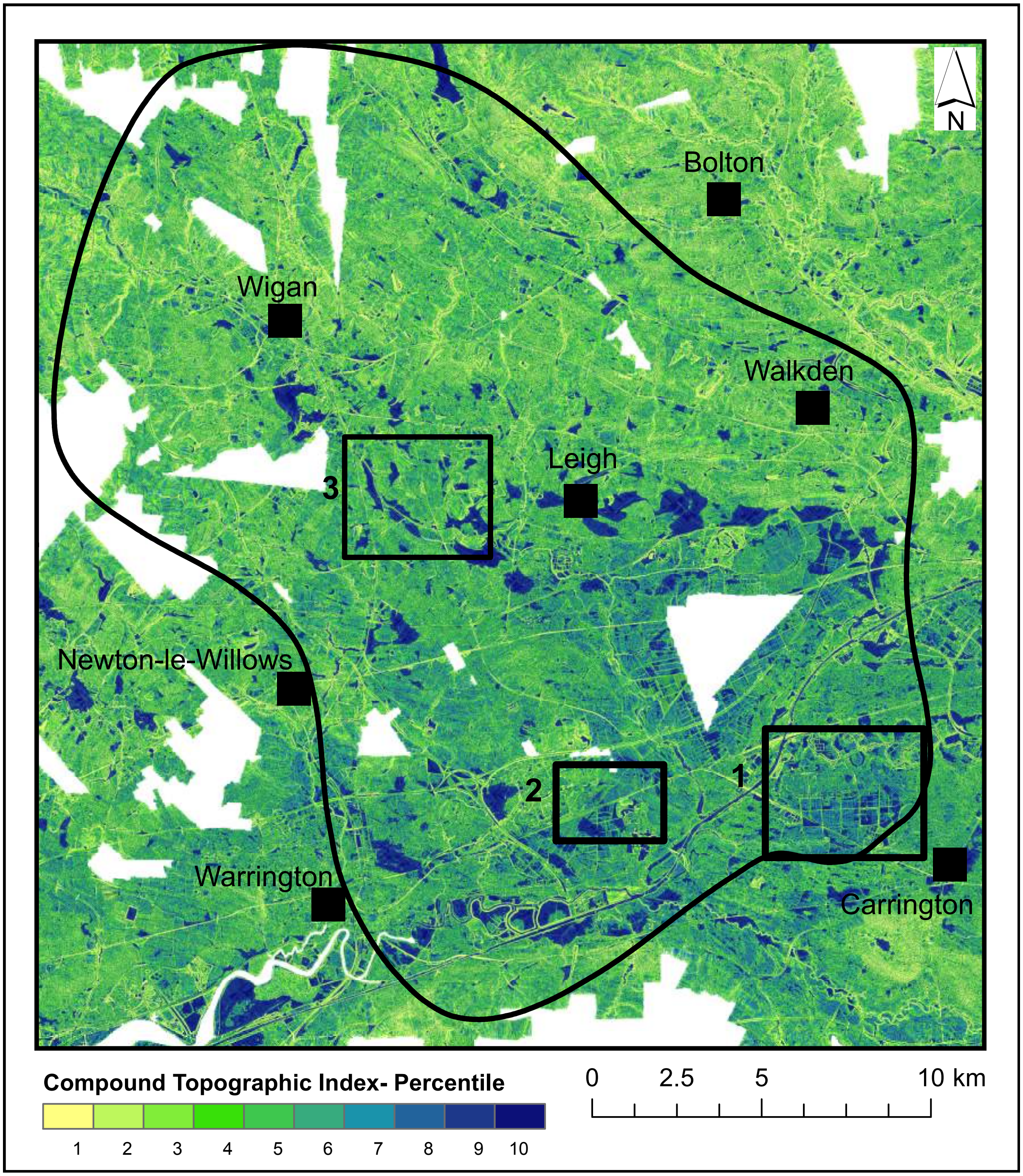

Figure 4. Regional Compound Topographic Index values. Black line is the boundary of th Great Manchester Wetlands Partnership. Boxes 1-3 refer to the subsets in Figure 5. White areas indicate the lack of LiDAR coverage.

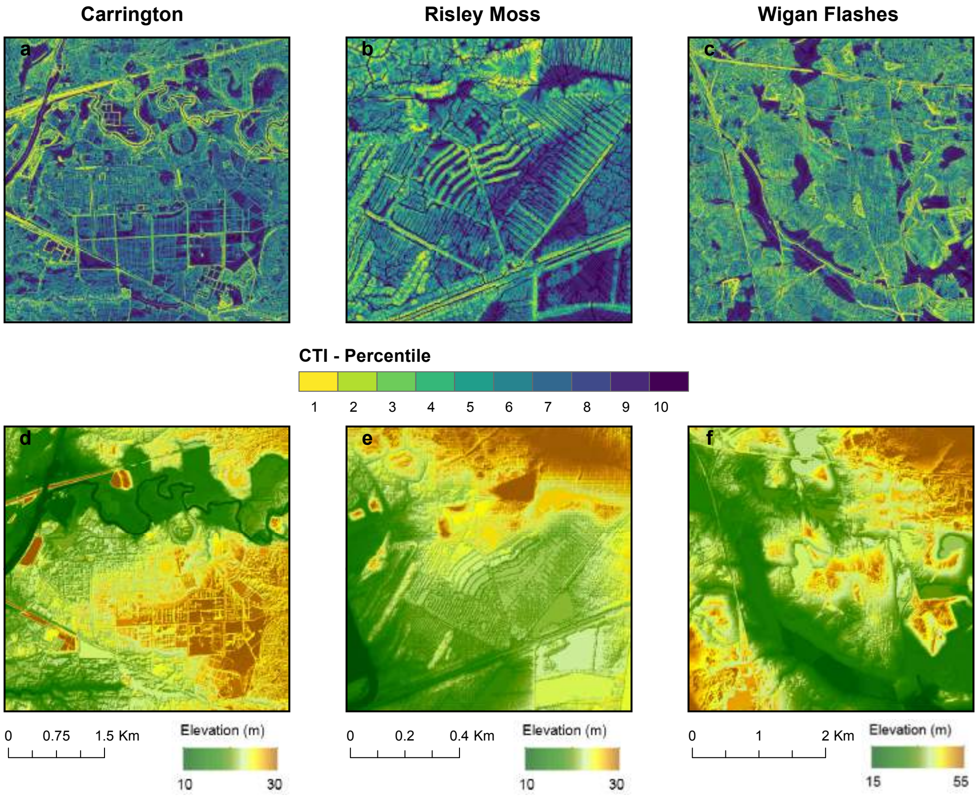

Figure 5. (a-c) Compound Topographic Index subset maps; (d-f) Respective DEM subsets.

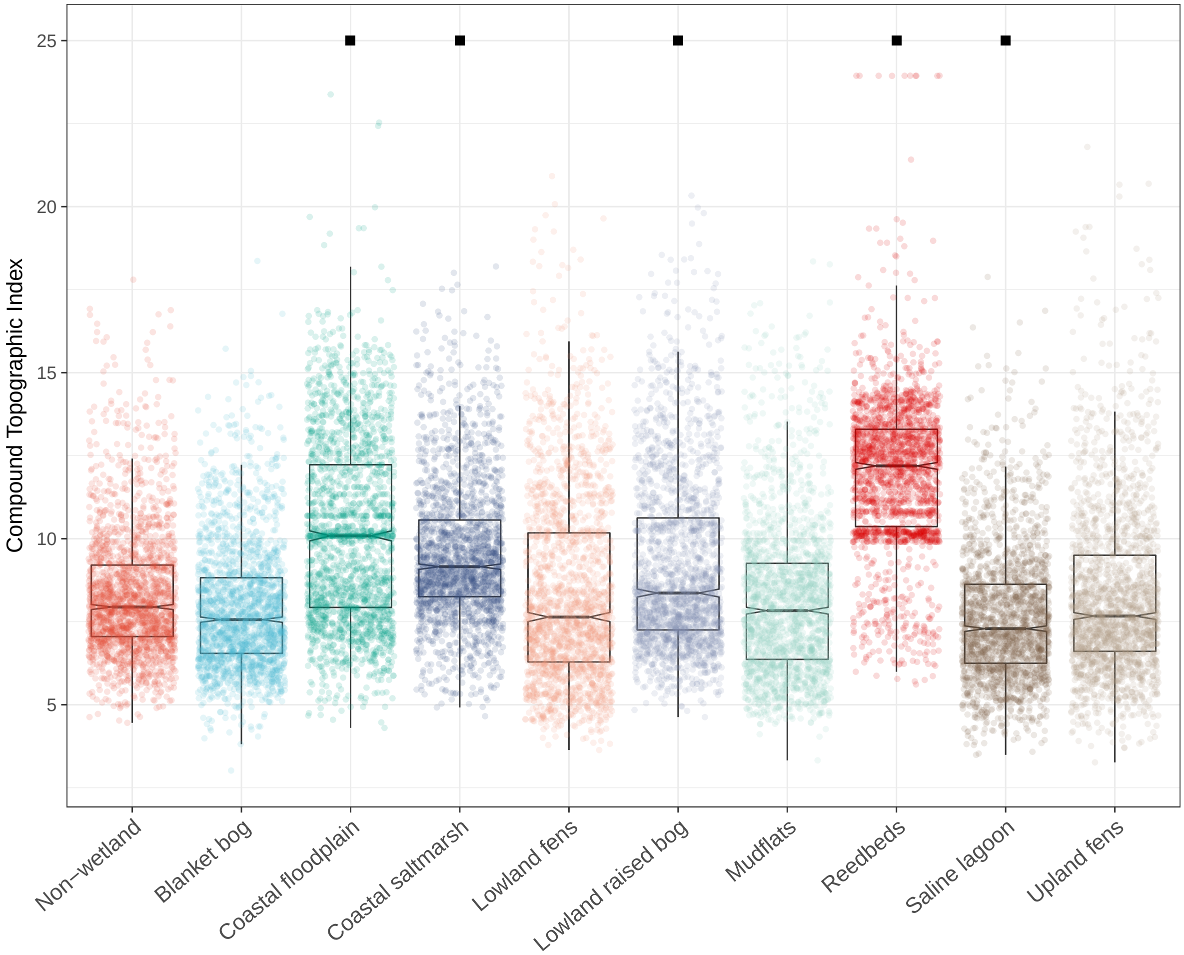

Figure 6. CTI values for 3000 random points per wetland category compared to non wetland. Black squares indicate a significant difference between the relevant class and non-wetland according to post-hoc Tukey's HSD test ($P < 0.05$)

3.2 Case Studies

3.2.1 Carrington Moss

Carrington Moss is a lowland raised peat bog in the south-west of the wider study area. The generally flat topography of this site has enabled a range of developments over the past 200 years, including night-soil disposal, agriculture, chemicals processing and sporting facilities. This area is now a priority location for new housing developments. A combination of water retentive peat soils and generally flat topography results in high potential wetness across much of this area. This is to be expected as active drainage is required to enable arable farming: the drainage ditch grid is visible in the bottom right of Figure 5a. The dominant peat soil unit does not display homogeneous CTI values, with southern and eastern segments featuring higher scores, highlighting the role of agricultural drainage. Furthermore, the sections immediately south of the River Mersey (basin visible in the top of Figure 5.d) have been heavily damaged by industrial facilities, demonstrating markedly lower wetness scores than the agricultural land. Wetland restoration in this area would therefore be most effective on the agricultural land, where the removal of drainage would facilitate water retention. Regardless of the underlying peat soils, the formerly industrialised sites have low water acculturation potential.

This case study highlights the potential of CTI-style models to identify small-scale drainage infrastructure that may inhibit restorations and re-wetting efforts. Identifying these features by manual surveying would be highly arduous and time-consuming. Simple topographic model allow the entire site to be assessed rapidly, so many planned works can be strategically directed.

3.2.2 Risley Moss

Risley Moss is a remnant segment of a lowland raised bog system that previously extended through southern Lancashire and northern Cheshire. The site consists of of woodland interspersed with meadows and degraded peat-based mossland for which it is nationally designated (*Risley Moss SSSI Designation*). The main dome segment is located in the centre of Figure 5b and 5e. The historically high water table at the site prevented agricultural development, and usage mainly focused on forestry and peat cutting. By the end of peat extractions works, the site was severely degraded, with the base heavily terraced and an elevated central section of drying peat unable to retain water. Since the 1970s, there has been a continued effort to increase the water table for this portion of the bog and prevent further drying of the site (Ross and Cowan 2003). This work has focussed on topographic modification by re-contouring the surface using bunds and scrapes along the dome surface. These can be seen in the "herring bone" pattern located at the centre of Figures 5b and 5e. These features aim to restore the peat by promoting water retention through accumulation in the hummocky terrain. The relative success of restoration work is visible in the CTI map. Large features established in the 1990s show a clear trench system (branching out from the dome centre, 5b and 5e), with pronounced variation between very wet trenches and drier ridges. These conditions are undesirable for restoration due to low potential for keystone species, such as Sphagnum mosses, to colonise either the dry crests or the deep pools (McNeil and Waddington 2003). Conversely, works undertaken more recently have a much shallower network of excavations (middle-right of Figure 5b), resulting in a more homogeneous wetness score. These areas are more favourable for Sphagnum moss species and exhibit reduced (or reducing) cover of dry tolerant plants, e.g.purple moor grass *Molinia caerulea*.

This case study displays the ecohydrological potential of simple topographic models, by highlighting the relative success or limitations of the restoration work. The scale of data employed here is particually relevant as the small-scale variations between the restoration works would be obscured under a coarse DEM (Rodhe and Seibert 1999). As microscale topography is an important factor for greenhouse gas flux and soil properties in peat bogs, LiDAR data has good potential for modelling these processes at higher resolutions (Rothwell and Lindsay 2007; Sundqvist et al. 2015).

3.2.3 Wigan Flashes

The Wigan Flashes in Figures 5c and 5f are patches of mining-induced subsidence that have developed into a series of open water ponds, wet grasslands, reed beds, and marshes. Initially, this subsidence resulted in the area accumulating pollution and being used as spoil heaps (Gemmel and Connell 1984). Over the last 20 years, clean-up efforts combined with de-industrialisation have transformed the habitat, leading to national designations for wildfowl assemblages and wetland habitats (Natural England 1990). ~~As newly formed wetlands, less than 50 years old, there has been minimal intentional degradation or development.~~ Many of the existing flashes display high CTI values indicating their high wetness potential due to the depressed terrain. Interestingly, many other plots feature comparable values including locations that would not typically be considered ideal wetland habitat, such as an industrial estate showing high values in the south-east (bottom-right) of Figure 5c.

In recent years, this site has become regionally important for bird and water vole communities (Champion and Ashton 2010; Powell and Milburn 2011). Due to their location, spanning both the urban landscape intersecting the Mersey and Ribble watershed and bridging the upland-lowland transitions, the Wigan Flashes may play a major role in ensuring connectivity for wetland species across these zones. Designing conservation corridors to enable species connectivity is a challenging endeavour, especially in urbanised environments; the provision of information on areas potentially receptive to developments is, therefore, desirable. However, in order to be successful, restoration ecology must be considered within the local social context. For the Wigan Flashes, a considerable amount of the works undertaken have been initiated by local wildlife groups and volunteers, such as the Wildlife Trusts. ~~Therefore, in order to be useful, scientific advice must be simple, understandable, and reliable.~~ During the completion of this work, the potential and limitations of using CTI maps was discussed with local operatives who found the simplicity and relatable nature of the outputs to be beneficial and appropriate for their work. This highlight the communication benefits of high-resolution yet simple models. These can be easily understood by the general public, providing evidence to encourage stakeholder buy in on restoration projects.

3.3 Potential Applications and Future Work

The restoration and maintenance of wetland habitat is a challenging and expensive undertaking. The provision of regional-scale spatially explicit data to inform conservation efforts is, therefore, beneficial (Mitsch and Wilson 1996). We envisage a number of ways in which the methods and outputs of this study may be of use. Firstly, high-resolution spatial information can inform decisions regarding the commencement of restoration work. Whereas many former wetland sites are known by local authorities, elucidating the potential receptiveness of these sites to remidiation can be an expensive and time consuming task when undertaken by field surveying. Models such as the CTI may offer a quick and low-coast alternative. This would be particularly appropriate where small-scale features (such as peat grips) affect hydrology, resulting in variable water retention over small areas; the Carrington and Risley Moss case studies would typify this. Given the expense of purchasing land and the often hit-and-miss nature of wetland reclamation works, it is essential that efforts be focused on plots which are most likely to succeed (Mitsch and Wilson 1996). The precise method of selecting plots would be determined by the objectives of the restoration work (e.g. species connectivity, carbon storage, flood prevention), yet in any case, easily accessible information on potential wetness would be a valuable resource to inform decisions (Bateman et al. 2013).

Secondly, the availability of high-resolution DEMs enables simulations of proposed developments to be undertaken. By modifying the original DEM to represent proposed developments, such as the blocking of drainage ditches, changes in surface flow and in the wetness potential can be rapidly assessed, thus ensuring the most appropriate allocations of efforts and funds.

Finally, wetlands support a large number of species, many of which require varying degrees of connectivity between habitat patches (Zinko et al. 2005). Focusing on known networks may overlook potentially important areas in unexpected or counter-intuitive locations. By employing broad-scale analyses, all potentially wet habitats can be evaluated and species distribution models adjusted accordingly.

Many studies have employed topographic information, often in conjunction with auxiliary or satellite data, to classify wetland habitats (Babbar-Sebens et al. 2013; Bwangoy et al. 2010). However, quantifying potential habitats is more complex, due to the uncertainty of projections. The approach developed here has a number of benefits over previous methods. Firstly, our approach is based on physical processes (water retention and accumulation) with a long hydrological usage, making the model transparent. Models developed in the future will therefore be comparable and unaffected by changes in e.g. land cover classification schemes.Secondly, by using a high-resolution DEM our models can be sense-checked easily, allowing areas with spurious results to be discarded; this would not be possible using an amalgamation of coarse-resolution auxiliary datasets e.g. (Schleupner and Schneider 2013; Van Lonkhuyzen, LaGory, and Kuiper 2004).

4 Conclusions

Wetlands are critical for biodiversity, hydrology and carbon storage. There is, therefore, growing interest in the restoration and creation of new wetland habitats. The provision of spatially explicit data to inform management is important to ensure the most ecologically and financially sound decisions are made and actions undertaken. In this study, we used high-resolution elevation data, in combination with regional land cover and soil maps, to model potential wetness of the wider Great Manchester Local Nature Improvement Area. The results showed generally higher values for existing wetlands, and also highlighted areas with high potential wetness, where restoration works may be successful, at both regional and local site scales. An increasing number of national mapping agencies are making LiDAR data freely available for scientific research, enabling improved prioritisation of wetland restoration and management.

5 Acknowledgements

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