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title: **Groundwater as an ecological supporting condition in raised bogs and the implications for restoration; an example from Clara Bog, Ireland**

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INTRODUCTION

The protection of wetland habitats that are sustained by regional groundwater flows is a basic tenet of the EU Water Framework Directive (WFD). Such systems are considered to be 'groundwater dependent terrestrial ecosystems' (GWDTEs) and understanding their 'environmental supporting conditions', which are primarily represented by their dependency on the prevailing hydrological regime, is essential for the conservation of wetlands.

Natural peatlands such as bogs are essentially wetlands that are, first and foremost, hydrological systems and their ecological functioning is primarily dependent upon the dynamics of the hydrological flows. However, raised bogs are generally considered to be isolated hydrological systems, separated from regional groundwater flows. Groundwater as a 'supporting' ecological condition is usually confined to the perimeter of a raised bog, where peat and underlying clay thin towards the margin, allowing regional groundwater and peat water to converge and mix, thereby giving rise to characteristic nutrient rich *lagg* zone vegetation. However, the relationship between groundwater and the raised bog body itself is complex and current research on Clara Bog, Ireland, suggests that groundwater provides some form of "support function" to the bog and that it should, in reality, be considered a GWTDE under the WFD.

SUBSIDENCE OF CLARA BOG

Clara Bog, located in midland Ireland, is one of Western Europe's largest and most important raised bogs, primarily because there are still considerable areas of active *Sphagnum* and peat growth. It also retains examples of soak systems, which have disappeared almost completely from raised bogs in Ireland, and are characterised by assemblages of rheotrophic and minerotrophic vegetation in an otherwise ombrotrophic environment. Though a Scientific Area of Conservation (SAC), Clara Bog has been extensively damaged in the past and it is estimated that the bog, as it exists now, covers less than half of the extent it once did in its pristine state. The bog may be considered to be two bogs, Clara Bog West and Clara Bog East, as a road, the Clara to Rahan 'bog road', bisects the wetland into two separate bog entities (Fig. 1). Marginal drainage associated with the bog road has resulted in the bog subsiding by up to 6m in the last 200 years (Bell, 1991), thereby permanently altering its hydrological dynamics.

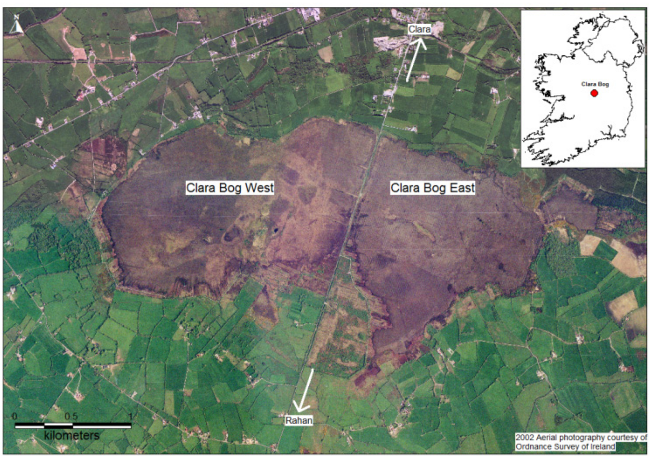

Figure 1. Location of Clara Bog.

In the recent past, the southern margins of Clara Bog West have been cut for turf. The removal of peat on the bog margin results in the development of 'face banks', which removes the natural lagg zone and results in vertical peat profiles marking an abrupt, and artificial, border to the main bog body. Coincident with such peat-cutting activities, is the development of marginal drains, which deepen as cutting extends into the bog. It is now known that Clara Bog West has subsided significantly since the early 1990's due to marginal drainage (Ten Heggler et al., 2004), thereby altering the surface level gradients on the bog which in turn alters the local flow paths that maintain sensitive rheotrophic ecotopes, such as the soak systems. The acrotelm capacity will therefore also be affected as its maintenance depends on shallow slope gradients (gradient must not exceed 0.3 m/100 m; Daly et al., 1994).

The southern sections of Clara Bog West have subsided locally by over 1 metre since 1991. Indeed, subsidence has now propagated as far as 600 m into the high bog (Ten Heggler et al., 2004; Regan, 2010). Coincident with this subsidence has been the development of bog pools and lakes due to differential rates of peat settlement. While drainage on the high bog (i.e. internal drainage) will affect the upper layers of the peat profile, drainage in cut-away sections by the high bog will reduce the piezometric head at the base of the peat profile and in the subsoil deposits underlying the peat (Ten Heggler et al., 2004). As a consequence, peat consolidation will concentrate in the deeper layers of the peat profile. Compaction of the peat implies an increase of the volume fraction of organic matter and a decrease of the vertical hydraulic conductivity, which in turn means an increase of the hydraulic resistance of the peat (Ten Heggler et al., 2004). Recent research (Regan, 2010) now indicates that subsidence is not solely due to simple consolidation of the peat body, but that external drainage has created a hydraulic connection between the high bog and regional groundwater flow, resulting in increased vertical flow movements. However, this "connection" is a localised phenomenon.

HYDROGEOLOGICAL FRAMEWORK OF CLARA BOG WEST

Clara Bog formed within a glacial basin and is bounded by an east-west trending esker on its northern side and is surrounded by an undulating topography consisting of glacial till on its eastern, western and southern sides. The predominant geological succession underlying the bog consists of (1) Carboniferous Limestone bedrock to (2) glacial till deposits of varying permeability to (3) low permeability lacustrine clay sediment, which is overlain by shelly marl in the central areas of the glacial basin. The lacustrine clay effectively acts as an aquitard, or "hydraulic barrier", by isolating the bog from regional groundwater flows in the subsoil (glacial till) aquifer and thus preventing downward leakage of water from peat to the till aquifer.

In section 2 the physical changes that have occurred on Clara Bog West, due to subsidence, since the early 1990's were briefly discussed. However, the surface level elevation of Clara Bog East has remained relatively static during the same time period implying it has not subsided. Significantly, Clara Bog East is almost wholly underlain by lacustrine clay, whereas Clara Bog West is not. The subsoil geology underlying the high bog of Clara Bog West is illustrated in Figure 2 and it can be observed that much of the western section of the high bog is underlain by glacial till. This subsoil aquifer protrudes through the lacustrine clay beneath the high bog at localised connections and, significantly, directly underlies the peat substrate in an area between the two most important ecological features of Clara Bog West, namely the Western Soak and Shanely's Lough.

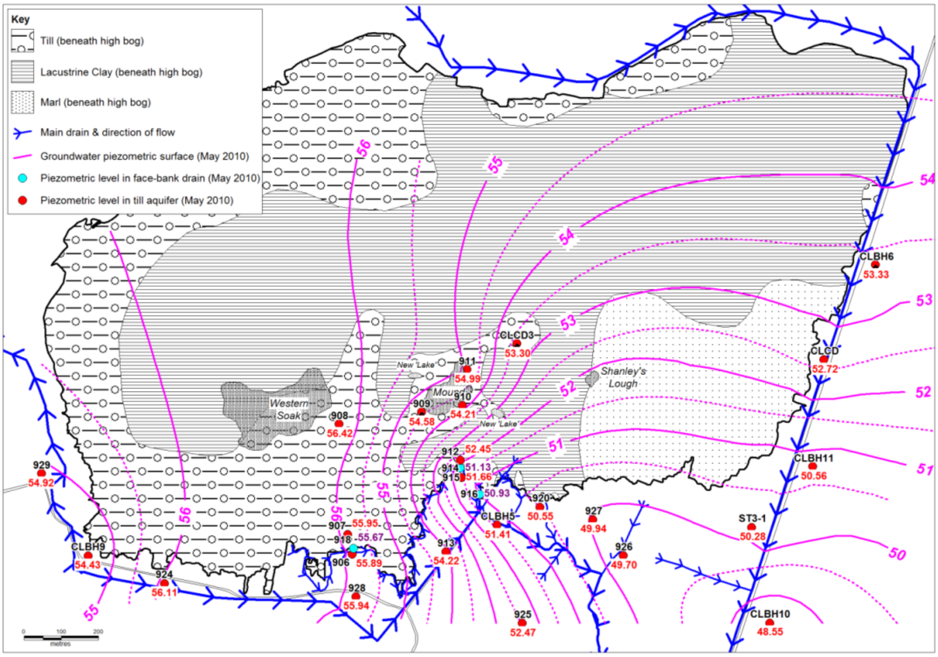

Figure 2. Clara Bog West: underlying subsoil geology, marginal drainage pattern and May 2010 piezometric contours in the mineral subsoil (till).

EFFECTS OF MARGINAL DRAINAGE

Groundwater discharge

In the mid 1990's, turf cutting on the southern margins of Clara Bog West accelerated to the extent that face-bank drains cut in so far as the underlying mineral subsoil (till). Agricultural drains in the southern regions of Clara Bog West were also deepened into the till deposits, some of which are connected to the face-bank drains bordering the high bog. To investigate the linkage between the marginal drainage and the groundwater levels beneath, and surrounding, the high bog, a number of piezometers were installed (Regan, 2010) in the glacial till aquifer. The piezometric surface of the groundwater table in the glacial till aquifer is illustrated on Figure 2. Hydraulic gradients are steep in the central area of the bog, where the glacial till underlies the peat, and groundwater flows in a south easterly direction from the Western Mound, which is a topographical high on the high bog, to the face-bank drains. A groundwater divide, broadly trending in a north-south direction, exists where the Western Soak occurs on the bog. The hydraulic gradient steepens considerably east of the Western Mound, and it has been found that where the hydraulic gradient is steep, the elevation at the base of the face-bank drains is below or coincident with the regional groundwater level (Regan, 2010). Elevated electrical conductivities (> 200 µS/cm) also occur in the face-bank drains where peat directly overlies till and the piezometric level is above that of the face-bank drain level (Figure 3). As such, where lacustrine clay is absent, the face-bank drains are a zone for groundwater discharge.

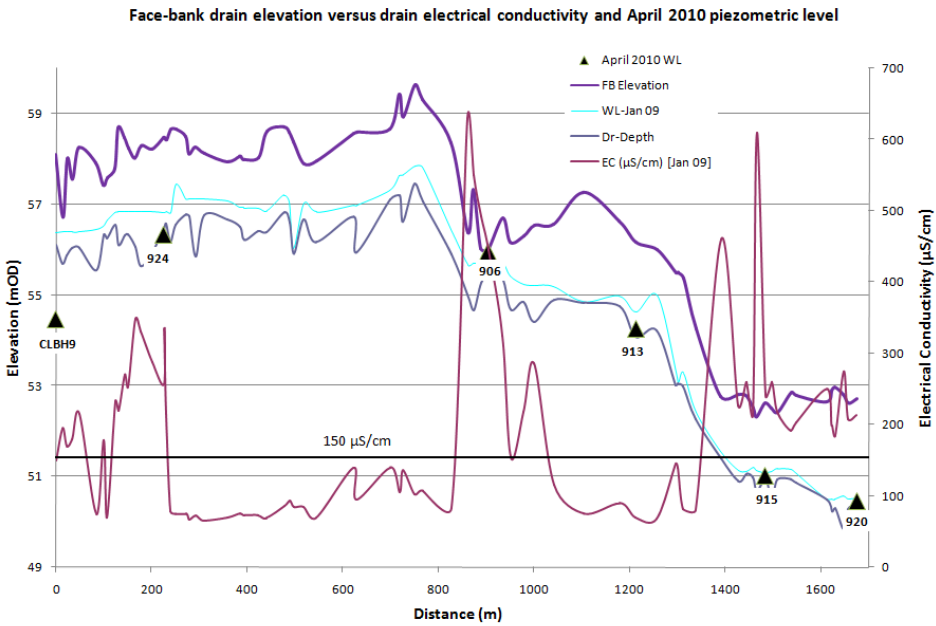

Figure 3. Face-bank drain elevation, April 2010 groundwater level, January 2009 drain water level and drain electrical conductivity values on southern margin of Clara Bog West.

Drop in regional groundwater table

There is evidence that marginal drainage has lowered the regional groundwater table at the margins of Clara Bog West, which has extended into the centre of the bog, coincident with the observed bog subsidence and bog pool/ lake development. A hydrograph from borehole CLBH5 (see location in Figure2), which is located on the southern margin of Clara Bog West, comparing the water level in the subsoil aquifer over similar time intervals in the years 1991/1992, 1996/1997 and 2009/2010 is presented in Figure 4.

It is clear from Figure 4 that the groundwater table has dropped significantly at CLBH5. Significantly, CLBH5 is located adjacent to an agricultural drain deepened into the till subsoil, which is the same till body which, in local areas, directly underlies the high bog, and within 60 to 160 m of the face-bank drains. The water level has decreased between c. 0.4 and 1.0 m from 1991/1992 to 2009/2010. Similar analysis of subsoil piezometric levels from boreholes surrounding Clara Bog West reveals little change in water level (Regan, 2010) over the same time period, implying that the lowering of the regional groundwater table is a localised phenomenon. However, a drop in regional groundwater level, between c. 0.3 and 0.5 m, has also been recorded at subsoil installation CLCD3 (Figure 3), which is located near the centre of the bog and where the lacustrine clay unit is absent (Regan, 2010).

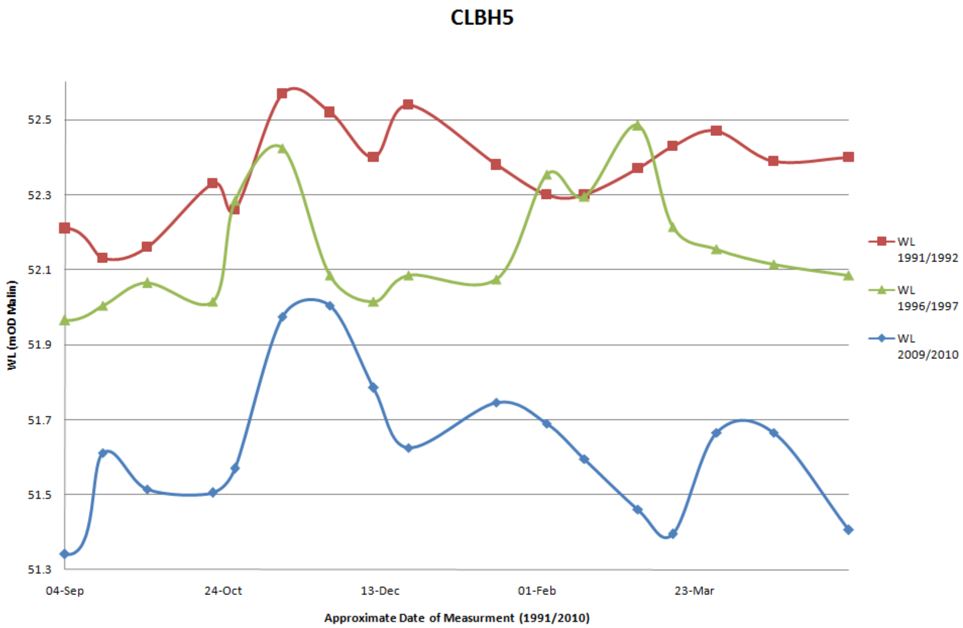

Figure 4. CLBH5 hydrograph of mineral subsoil water levels from 1991/1992, 1996/1997 and 2009/2010. Note: all levels are referenced to the same datum to avoid levelling inaccuracies.

SUMMARY

Traditionally, raised bogs are considered to be isolated hydrological systems, separated from regional groundwater flows. However, research at Clara Bog has indicated a greater dependency of raised bogs on groundwater, especially in the absence of lacustrine clay. In the recent past, subsidence of the bog has coincided with a local drop in the regional groundwater table, induced by marginal drainage of the aquifer underlying the main bog body. Evidence now suggests that if regional groundwater is affected, there is a corresponding impact on the raised bog peat vertical drainage. The hydrogeological monitoring and analysis of Clara Bog West to date indicates that water losses from the main bog body are not simply a result of lateral seepage of water through the peat profile at the bogs margins but are also a result of vertical water losses in the peat profile in the main bog body. As such, though groundwater is not directly supporting ecology on the high bog, the hydrostatic pressure of groundwater is crucial in maintaining a high water table in the bog. Where lacustrine clay is absent, and the bog is hydraulically linked to regional groundwater, marginal drainage adjacent to the bog (face-bank drains), and outside the bog (agricultural drains), creates pathways for vertical water movement, thereby reduces the hydraulic gradient and resulting in drainage of moisture from peat in the high bog. Restoration measures to arrest subsidence of the high bog are therefore dictated by understanding, and quantifying, these drainage pathways.

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