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The impact of pumped water from a de-watered Magnesian limestone quarry on an adjacent wetland: Thrislington, County Durham, UK

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High pH, sediment-rich runoff from a quarry constrains floristic diversity in an adjacent wetland.

Abstract

Although quarrying is often cited as a potential threat to wetland systems, there is a lack of relevant, quantitative case studies in the literature. The impact of pumped groundwater discharged from a quarry into a wetland area was assessed relative to reference conditions in an adjacent fen wetland that receives only natural runoff. Analysis of vegetation patterns at the quarry wetland site, using Detrended Correspondence Analysis and the species indicator values of Ellenberg, revealed a clear disparity between community transitions in the quarry wetland and the reference site. Limited establishment of moisture-sensitive taxa, the preferential proliferation of robust wetland species and an overall shift towards lower species diversity in the quarry wetland were explicable primarily by the physico-chemical environment created by quarry dewatering. This encompassed high pH (up to 12.8), sediment-rich effluent creating a nutrient-poor substrate with poor moisture retention in the quarry wetland, and large fluctuations in water levels.

Keywords: Limestone quarry; Wetland; High pH; Alkaline

1. Introduction

Predicting impacts of limestone quarrying activity on adjacent wetlands is a highly uncertain process, for at least two reasons: (i) the heterogeneity of hydrological processes in many limestone terrains (e.g. Smart et al., 1991), and (ii) the inherent difficulty in distinguishing between the sensitivity of plant communities to change in water table conditions and water quality perturbation (e.g. Wheeler and Shaw, 1995).

Uncertainties in prediction of impact of quarry development often result in a highly precautionary approach being taken by regulators in relation to proposed mineral developments. In such cases, the onus of proof is usually placed on the mineral developers, who are charged with providing quantitative evidence that quarrying will not give rise to unacceptable hydrological, or hydrochemical and/or ecological impacts (e.g. Finlinson and Groves, 1994; Wardrop et al., 2001).

The impacts of limestone extraction on the surface water and groundwater environment have been widely documented and discussed (e.g. Roy Waller Associates Ltd., 1991; Gilman, 1994; Rust Environmental Ltd., 1994; Thompson et al., 1998; Hobbs and Gunn, 1998;

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Mitsch and Gosselink, 2000; Adams and Younger, 2001). Impacts of limestone extraction on wetlands can encompass hydrological issues (e.g. flow derogation or augmentation typically associated with pumping operations), hydrochemical changes (resulting from accidental spillages of oils etc., or from the generation of high pH leachates where lime kilns are co-sited with limestone quarries), and problems associated with increased sediment loadings entering receiving water bodies. However, published accounts of the nature of such impacts has to date been largely restricted to qualitative accounts and the conjectural assessments of possible interactions between quarrying activity and the surrounding hydrological environment. For instance, Finlinson and Groves (1994) have suggested that as many as 100 of the 3750 designated Sites of Special Scientific Interest (SSSIs — a UK legal notification which protects sites of wildlife or geological importance) in the UK may be at risk from the de-watering effects of proximate quarrying operations, although details of the nature and magnitudes of risks are not specified.

This paper describes an integrated assessment of the effects of Magnesian limestone quarrying on hydrological, hydrochemical and ecological processes in wetland environments that receive effluents from a limestone quarry. This study aims to quantify the nature and magnitude of impacts of dewatering on a natural wetland through comparison with an upstream reference site. Besides providing a quantified example, the methodology used in this study represents a potential model for future impact assessments at other sites. Furthermore, the study assesses the conservation value of the impacted communities and the possible ancillary water quality benefits provided by wetlands in receipt of alkaline discharges.

2. Materials and methods

2.1. Study site

At Thrislington Quarry, County Durham, UK (54°41′12″ N, 1°31′56″ W), water pumped from a quarry working the Magnesian Limestone and Basal sands (both of Permian age) is discharged into a natural wetland adjacent to the operating area. Directly upstream of this quarry wetland is an unaffected SSSI fen wetland area (hereafter referred to as the ‘reference site’), which provides a comparison from which the hydrological, hydrochemical, and ultimately, floristic influence of pumped effluent disposal in the quarry wetland can be assessed.

Fig. 1 shows the wetland study site, which lies to the west of the quarry void and associated calcination (i.e. lime-burning) works. The wetland lies in a low-lying glacial meltwater channel cut through the Magnesian Limestone escarpment, the base of which is lined with low-permeability glacial till. The wetland, which supports dense calcareous fen vegetation, is bisected by a railway embankment, which effectively separates the reference site from the quarry wetland. The quarry wetland receives pumped groundwater, which is mixed to varying degrees with other sources of works runoff, including leachates from calcination plant wastes (which have extremely high pH values). The groundwater pumped from the quarry is itself a mixture of two sources: (i) limestone groundwater which flows downwards to a sump sunk into the underlying Basal Sands, and (ii) mine water pumped from an old colliery shaft (Thrislington Jane Shaft), which pierces Carboniferous-age Coal Measures to the north of the workings. The mine water is used as process water in the quarry processing plant.

Water levels within the quarry wetland area are regulated by a sluice gate into the adjacent water body (marked as ‘South Pond’ in Fig. 1). The vegetation of this quarry wetland has been allowed to establish and succeed in a spontaneous fashion (sensu Pyšek et al., 2001) over lime spoil which was previously deposited in the area. Prior to quarrying activity, archival evidence (Mayes, 2003) shows the quarry wetland to be part of a larger mire unit which, along with the reference site, entirely covered the glacial meltwater channel.

The reference site to the west of the railway embankment occupies 12.9 hectares, and is not subject to any ‘active’ vegetation management (i.e. grazing, mowing, or burning). The principal water sources for this fen wetland arise from a calcareous flush area north of the site and an area of made ground (e.g. quarry and coal mine spoil) to the north east (Fig. 1). Outflow from the reference site occurs via a culvert beneath the railway embankment, providing a further source of water to the quarry wetland. This culvert serves as the principal regulator of levels in the reference site, with a fairly consistent outflow of between 2 and 5 L s^{-1}. Flow is always southerly, from the reference site through the culvert, and water never flows back from the quarry wetland into the reference site. This ensures that the hydrological integrity and separation of the reference site from the quarry wetland is maintained. The reference site can thus be viewed as being ‘hydrologically managed’, in that the culvert is designed to ensure a consistent outflow from the site. Archival evidence (e.g. vegetation surveys, maps and aerial photographs: see Mayes, 2003; Graham, 1988) shows the hydrology and vegetation of the reference site to have been relatively stable over recent decades. Although it is impossible to gain true control conditions at such scales outside of the laboratory, these ‘reference’ conditions are typical of calcareous mires in the local region (e.g. Graham, 1988) and thus provide a suitable

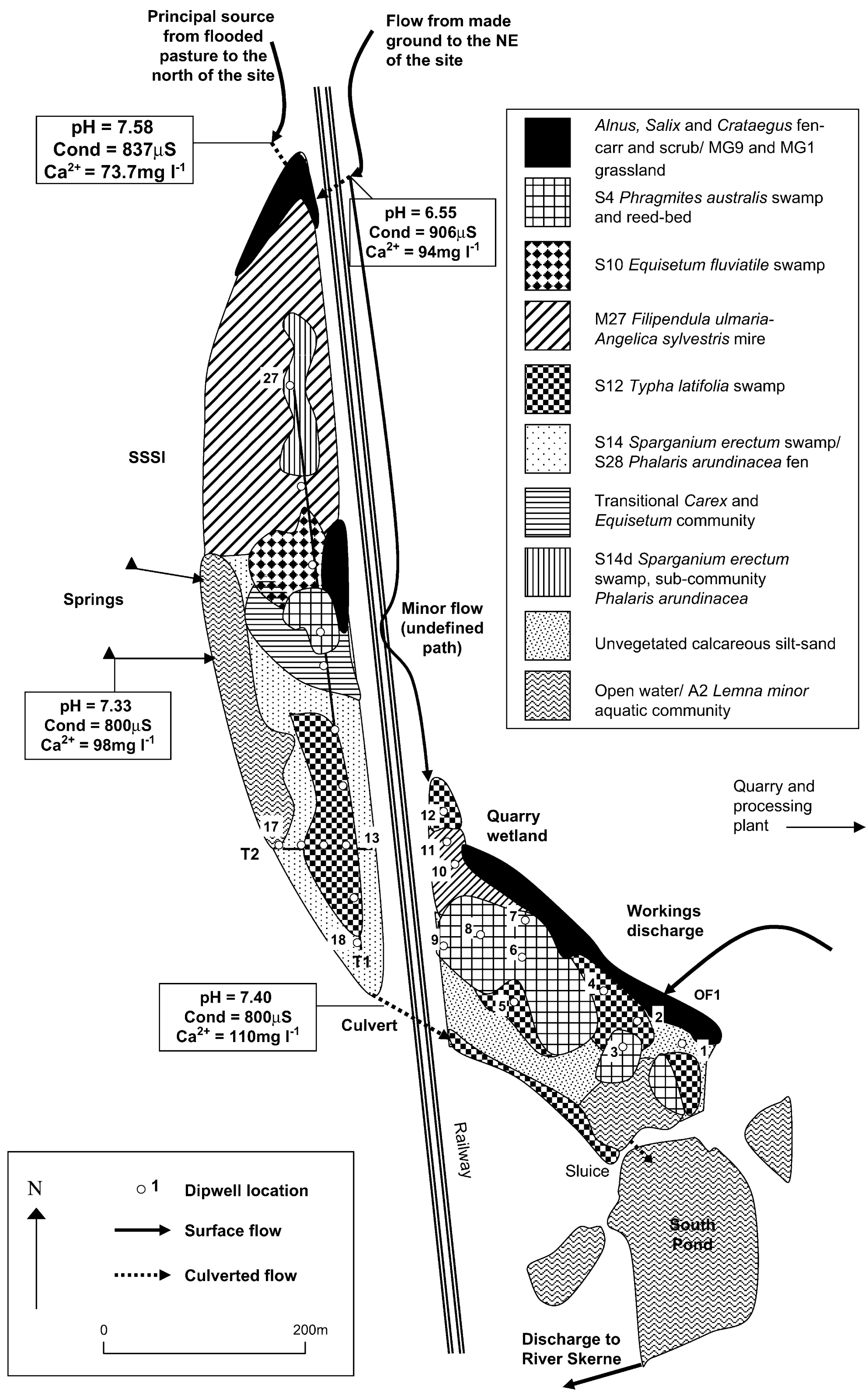

Fig. 1. Location map of the quarry wetland and reference site highlighting the nature of the source hydrology and major vegetation communities across the site. T1 = transect 1 and T2 = transect 2 across the reference site.

and immediately proximate comparator from which to assess the impact of quarry effluent on the downstream quarry wetland.

2.2. Physico-chemical, vegetation and statistical analysis

A monitoring network of 27 dipwells (14 in the reference site, 13 in the quarry wetland) was laid out (in March 2000) in transects designed to provide profiles across the principal moisture and vegetation gradients (Fig. 1). Water levels were monitored weekly over the period April 2000–November 2001 along with sampling of major physico-chemical parameters (pH, electrical conductivity, *Eh* and water temperature) in all dipwells, and the quarry effluent source using a Myron L Company six-parameter Ultrameter.

Monthly water samples were collected from selected dipwells over the period October 2000 to September 2001. For each sample, two polypropylene bottles were filled, one of which was acidified (for cation and metal analysis) and the other left untreated (for anion analysis). All samples were filtered using 0.45-μm cellulose nitrate filters and were analysed (always within one week of sampling) for major anion and cation species using a Dionex 100 Ion Chromatograph. Fe and Mn (preliminary analyses showed other metals such as Al, Cu, Zn, Pb, Cd, and Ni to be consistently below detection limits) were measured using a Pye Unicam Atomic Absorption Spectrophotometer (AAS). Sample alkalinity was determined in the laboratory within 2 h of sample collection by titration against 0.05 M H_2SO_4. Reliability of sample analyses were tested by charge balance calculations. An electro-neutrality within $\pm 5\%$ was considered to be of suitable accuracy. The wetland surface samples were supplemented by data obtained from the quarry operators who undertake monthly monitoring of groundwater chemistry in observation boreholes around the site, including the two main sources of water for the quarry wetland.

Physico-chemical analyses of substrate characteristics were carried out to assess transitions in nutrient availability and physical attributes of the wetland substrate across the site. Soil moisture in surface horizons (1–10 cm depth) was measured on the day of sample collection through heating 11–20 g sample at 105 °C until constant weight of samples was reached (see Allen et al., 1989). One hundred and twenty-four samples were taken from areas of differing wetland character (e.g. from uncolonised quarry sediment, reed-beds, herbaceous fen) under dry conditions (defined as ≤ 2 mm precipitation in the 20 days prior to sampling). Organic content of the wetland soils was estimated from the loss on ignition (LOI) of 5 g of dry sample held at 550 °C until constant weight was achieved, following the standard method of Allen et al. (1989). Sediment samples from the top 30 cm of the soil profile were taken at 20 locations across the quarry wetland and the reference fen wetland site for nutrient extraction and elemental analysis. Extracts were made from 5 g (1 g for N extraction) of substrate samples which were air-dried and coned and quartered from the bulk samples. Ca, Mg, Fe and Mn were extracted using 200 ml of 0.5 M ammonium acetate and concentration estimated via AAS; Na and K with the same extractant by flame emission spectrophotometry, inorganic P via colorimetry using 100 ml 0.5 M $NaHCO_3$ extractant and N using 2 M KCl followed by semi-micro Kjedahl distillation procedure (following the standard methods of Allen et al., 1989).

Sedimentation rate in the quarry wetland was measured using a series of graduated (to 1 mm) sedimentation rules which were hammered into underlying coarse sand fractions in areas around the quarry outfall that undergo periodic sediment deposition. Sedimentation was recorded every two weeks between December 2000 and November 2001. Vegetation surveys were carried out in summer 2001, comprising species identification and visual estimates of species percentage cover in 4-m^2 quadrats at each of the 26 dipwell locations. This quadrat size was deemed suitable following preliminary site assessments and follows the guidelines of Kent and Coker (1992). A survey of vegetation in marginal areas of the quarry wetland was carried out in August 2001. This supplementary survey consisted of 17 randomly placed 4-m^2 quadrat locations within stratified sampling areas outside of the dominant monospecific stands of *Phragmites australis*[1] and *Typha latifolia*. Here the objective was to identify species composition of littoral areas and pioneer communities on the more open calcareous silty-sand substrate.

Analysis of quadrat data was undertaken using Detrended Correspondence Analysis (DCA) to investigate the main divisions and affinities within the vegetation data using CANOCO (ter Braak, 1988). Log transformations of cover data were executed so that data conformed approximately to a Gaussian (normal) distribution, with no down-weighting of data for rare species. Interpretation of ordination data is aided by (1) relating the surveyed communities with the archetypal communities of the National Vegetation Classification (NVC — a phyto-sociological classification system of British vegetation types, whereby each vegetation type has a unique 'code': Rodwell, 1991) using TABLEFIT (Hill, 1996) and (2) integrating revised Ellenberg *F*-values (Ellenberg, 1988, as described by Hill et al., 1999) into the ordination analysis. Vegetation indicator (*F*-) values to describe environmental preference of individual species have been successfully applied for interpreting

[1] Nomenclature follows Tutin et al. (1992) for vascular plants.

vegetation patterns and transitions under changing hydrological conditions (e.g. Gremmen et al., 1990; ter Braak and Wiertz, 1994). The *F*-values are still, however, limited by the general coarseness of the scale. While it can be a constraint on analytical power in communities where species are confined to a narrow range on the scale, it is the very crudeness in scale that makes the assessments so generally applicable and hence useful. At Thrislington, *F*-values dispersed evenly between 4 (*Hordeum murinum*) and 11 (*Lemna minor*) on the scale give greater scope for assessing moisture gradients within the vegetation data.

3. Results

3.1. Vegetation

Fig. 2 presents DCA by quadrat location for all vegetation monitoring points across both the reference and quarry wetlands, with superimposed quadrat-averaged revised Ellenberg *F*-values. The data show a clear transition in community type with moisture condition along axis 1 of the DCA plot (which accounts for 12.2% of the variance within the data). This hydrological gradient ranges from monospecific *Typha latifolia* reedswamp (dw16, dw15, dw18) to more diverse *Typha latifolia* and *Sparganium erectum* communities (dw14, dw19, dw21). These narrow-leafed emergent communities grade into transitional littoral and herbaceous fen (e.g. *Equisetum fluviatile* swamp, *Phalaris arundinacea* fen and *Filipendula ulmaria*-*Angelica sylvestris* mire communities) at sites above the water line (i.e. the free water surface termed ‘water table’ when below the ground surface) on the reference site (dw23, dw25, dw26). The gradation toward drier communities is reflected in the presence of plant communities that are most clearly allied with grassland, herbaceous vegetation typically associated with disturbed areas (e.g. *Epilobium hirsutum* and *Urtica dioica*-*Cirsium arvense* tall herb communities) and underscrub (e.g. *Rubus fruticosus*-*Holcus lanatus* underscrub community) in the quarry wetland (e.g. locations M1b, M1c, M2a, M7b). A separate cluster of *Phragmites australis* reed-bed communities (dw1, dw2, dw3, dw24) show these isolated, species-poor communities as being distinct from the principal moisture-controlled vegetative transition across both sites.

This transition from communities indicative of ‘wet’ conditions to ‘drier’ communities along axis 1 represents the dominant division in the flora of the site and is reflected by the changing quadrat-averaged revised Ellenberg *F*-values on Fig. 2. The nature of the correlation between *F*-value and DCA axis 1 score is

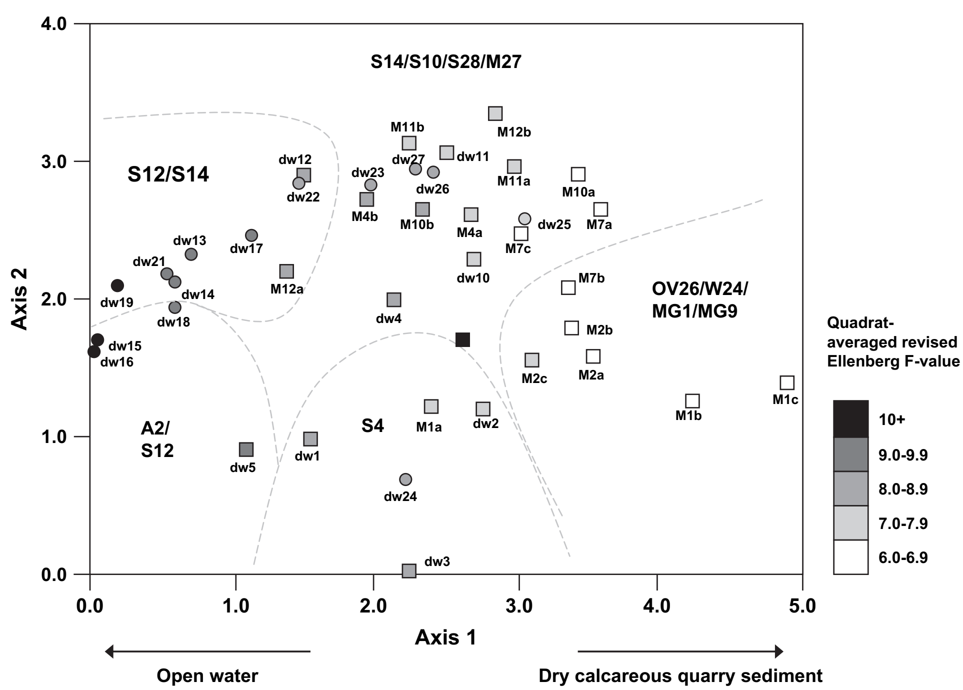

Fig. 2. DCA by quadrat location showing vegetation community gradation on the quarry wetland (square) and reference site (circle). Quadrat key: dw, dipwell; M, marginal quadrat. Community clusters are shown with reference to NVC codes from TABLEFIT output where data shows a ‘good’ or ‘very good’ fit with the archetypal communities (i.e. score >70). NVC codes: S4, *Phragmites australis* reed-bed (sub community: a, *Phragmites australis*); S10, *Equisetum fluviatile* swamp; S12, *Typha latifolia* swamp (sub communities: a, *Typha latifolia*; b, *Mentha aquatica*; c, *Alisma plantago-aquatica*); S14, *Sparganium erectum* swamp (sub communities: c, *Mentha aquatica*; d, *Phalaris arundinacea*); S28, *Phalaris arundinacea* fen; A2, *Lemna minor* aquatic community; M27, *Filipendula ulmaria*-*Angelica sylvestris* mire; OV26, *Epilobium hirsutum* tall herb community; MG1, *Arrhenatherum elatius* grassland; MG9, *Holcus lanatus*-*Deschampsia cespitosa* grassland; W24, *Rubus fruticosus*-*Holcus lanatus* underscrub.

very strong ($R^2 = -0.763$) highlighting a clear, significant (at the $p = 0.05$ level) linear correlation. This relationship can be further defined by correlating the DCA axis 1 scores with measured hydrological variables where available from dipwell records. Debate persists over which components of hydrological variation are most salient in affecting vegetation composition of wetland areas (e.g. Wheeler and Shaw, 1995, 1996; Wheeler, 1999), and as such there is no single hydrological parameter (or collective parameter) which is sufficiently well correlated to render it useful in predicting the vegetation of a given locality within the wetlands. However, strong linear correlations between mean annual water table level and DCA axis 1 scores ($R^2 = -0.74$) allows the gradation along moisture gradients at the site to be related to measured water table parameters. While this exercise does not endeavour to assign water table limits to vegetation communities (nor to take account of more intricate water level fluctuations) it does describe the general eco-hydrological transition over the site. This is important when comparing coarse patterns in vegetative transition across moisture gradients between the quarry wetland and reference conditions. Fig. 3a and b display hydrological limits of occurrence for the broad community classes of the reference site and quarry wetland and show a clear difference in vegetative transition between the two wetlands. These patterns of transition are estimated by transposing water table parameters on axis 1 of the DCA in Fig. 2 so that approximate limits of community occurrence for all quadrat locations (and not just those with a monitored record) can be assessed.

The vegetative transition on the reference site is clearly defined as shifting from tall emergent *Typha latifolia* (S12) communities into transitional hydrophyte assemblages at the water line (S10, S28, S14d), and finally to herbaceous fen (M27/OV26) in areas where mean water table is typically 21–30 cm on average below ground surface. This contrasts with the quarry wetland where *Phragmites australis* (S4) and *Typha latifolia* (S12) reed-bed predominate across a wide range of moisture conditions. Herbaceous fen conditions occupy a relatively narrow moisture niche in the quarry wetland and grade rapidly towards scrub and grassland communities in areas where the corresponding water table condition (ca. −15 to −30 cm) on the reference site still supports herbaceous fen communities. The data therefore suggest that environmental influences in addition to average moisture condition define the differing community gradations between the quarry wetland and reference conditions.

3.2. Hydrological regime

Hydrological regime was found to contrast clearly between the two wetland cells. Fig. 4 illustrates the stable nature of the regime in the reference site controlled by precipitation and summer recession in levels, compared to the rapidly fluctuating, high-amplitude regime in the quarry wetland. This relative stability in the reference site reflects the consistent inputs of source waters and the steady outflow through the culvert at the southern tip of the site. The annual range of levels experienced at each monitoring location is similar, typically ranging between 10 cm and 40 cm in both the relatively wet and dry years. Precipitation was seen to account for between 42% (dw27) and 74% (dw16) of the variance (in simple multiple linear regression alongside air temperature and calculated evapo-transpiration) within the dataset.

In contrast to the consistent and predictable hydrological regime in the reference site, the quarry exhibits a ‘flashy’ regime, characterised by frequent, abrupt and relatively large fluctuations in water level (Fig. 4). The observed range in levels in each of the study years was between 20 and 50 cm. The more variable regime highlights the influence of pumping operations and sluice gate release across the whole quarry wetland. Response to major precipitation events and the general pattern of high winter water table and lower summer levels are also clearly apparent in the quarry wetland. However, this response is complicated by the fluctuating regime and clear inter-annual differences in drawdown during the growing season. In contrast to the 41–74%

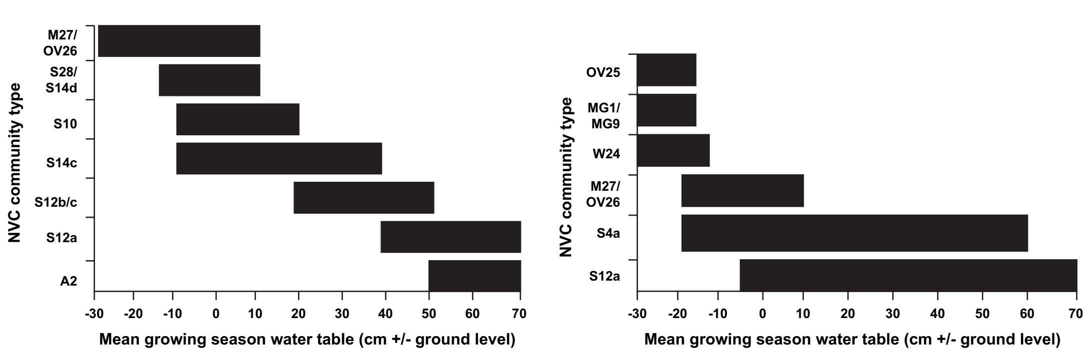

Fig. 3. a (left) and b (right). Schematic diagram displaying the approximate limits of occurrence of the main plant communities with respect to average water table condition for the reference site (4a) and quarry wetland (4b). NVC codes: see legend Fig. 2.

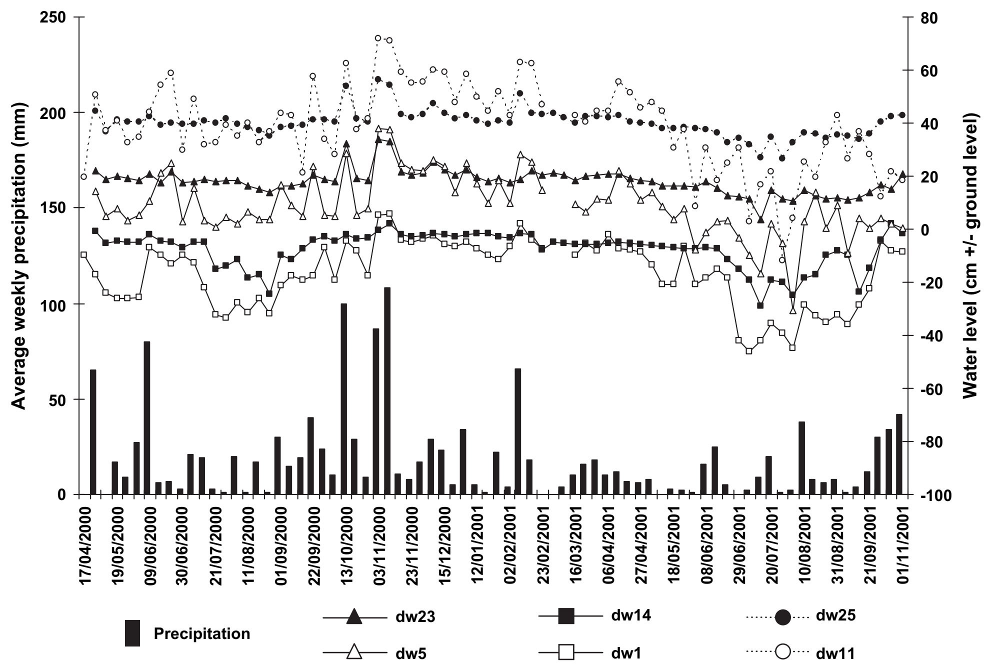

Fig. 4. Rainfall and water table levels in the quarry wetland (open symbols) and the reference site (black symbols), April 2000-November 2001.

of the variance that could be solely attributed to precipitation in the reference site, only 11–34% of the variance in quarry wetland locations could be accounted for by precipitation.

3.3. Sedimentation

There are two main implications of elevated sediment accumulation in the vicinity of quarry workings for the vegetation assemblages on the Thrislington site: (i) burial of the seed reservoir and (ii) hindrance of seedling establishment via smothering of chlorophyllous tissue of plants. Sedimentation rate was seen to vary between 0.2 and 8.9 cm $year^{-1}$. The areas of significant accumulation occurred in a relatively narrow area flanking the workings outfall channel. Within these areas vegetation cover is sparse, with only *Phragmites australis* and *Typha latifolia* found in consistent abundance. These species are unlikely to be hindered by seed or leaf tissue smothering (Haslam, 1965; Brown, 1983) due to their large narrow-leafed emergent form and rapid growth rates (documented to be as high as 1–4 cm day^{-1}; Haslam, 1972). The influence of sedimentation on species establishment and proliferation can thus be considered of minor importance across the quarry wetland in general.

3.4. Water chemistry

Table 1 presents major physico-chemical parameters (pH, conductivity, temperature, *Eh*) and major ion content for representative surface monitoring locations and groundwater monitoring locations across the Thrislington site. Water quality across the hydrological gradient of the reference site was observed to show little variability over time. Variations in pH, conductivity and *Eh* were slight, with samples from open water locations (dw11–21) and interstitial samples (dw21–27) displaying similar hydrochemical facies (typical of calcareous fen), with pH ranging between 6.1 and 8.4, and Ca levels between 110 and 220 mg L^{-1}. Nitrate and phosphate levels in surface waters did not vary spatially across the reference site (NO_3 = 0–30 mg L^{-1}; PO_4 = 0–3.5 mg L^{-1}). These waters are fairly eutrophic owing to the source water arriving from pasture to the north and north-east of the site.

Hydrochemical analyses show the quarry workings effluent (OF1) to have pronounced elevations in pH (up to 12.75) and electrical conductivity (up to 5994 μS cm^{-1}), Na^+, SO_4^{2-}, Mg^{2+} and K^+. The elevations in Na^+, SO_4^{2-}, Mg^{2+} and K^+ over adjacent wetland surface waters are consistent with the major ion composition of source water (BH13b and TJ: Table 1), and are a likely result of stone crushing and weathering of de-icing salts used in quarry operations. However, clear differences between source and discharge pH and conductivity values occurred episodically. Average pH in the boreholes (BH13b and TJ) was 7.8 with a maximum value of 8.0 whilst OF1 levels (mean pH of 8.8) reached values in excess of 10.5 on seven occasions over the monitoring period. The influence of the high pH effluent on the quarry wetland creates a distinct hydrochemical and sedimentological gradient across the cell, ranging from levels averaging around pH

Table 1
Typical summer major ion analysis for selected surface and ground-waters at Thrislington

Location[a]	pH	pH (max)	E.C.	*Eh*	Temp.	Total alkalinity	Ca	Mg	Na	K	Cl	NO_3	PO_4	SO_4	Fe	Mn
BH13b	7.9	8.0	1080			438	101	41.4	64.3	2.81	155	0.1	<0.1	188	0.02	<0.01
TJ	7.8	8.0	1630			383	132	69.2	256	16.7	155	1	<0.1	484	0.02	<0.01
OF1	8.83	12.75	1714	55	9.08	80	141.1	52.1	82.2	51.2	120	38.2	2.9	285	5.7	0.03
dw1	9.16	10.26	1518	62	9.12	131	95.2	174.2	29.6	18.9	104	34.9	–	289.5	0.05	0.01
dw2	9.12	9.83	2119	75	9.00	36	33	208.2	45.1	20.9	150.3	39	–	307.5	0.019	0.01
dw3	9.02	10.05	1288	−10	10.09	106	120.5	110.2	100.5	21.6	185	41	–	421.6	0.02	0.01
dw4	8.52	9.51	1151	−11	10.47	101	121.5	79.2	62.3	17.2	177.7	45.2	–	165.2	0.159	–
dw5	7.53	8.60	1028	−50	10.2	161	120.4	87.2	55.1	16.5	165.2	52.3	–	154.6	–	–
dw11	7.46	8.60	1135	−94	10.29	217	135.2	117.1	52.9	18.1	184.2	45.5	–	184.2	0.568	0.02
dw12	7.44	8.66	1120	−81	10.49	167.5	130	102.2	68.6	12.1	256.2	54.2	–	179.9	0.228	0.02
dw13	6.97	7.81	728	−56	12.48	250	119.3	33.3	30.9	16.4	75.1	16.5	–	78	0.233	–
dw14	7.06	7.79	773	−44	11.28	230	185	49.4	85.1	10.8	72.1	0.8	1.2	174	0.228	–
dw18	7.11	7.85	806	−37	12.10	203	168.4	44.5	93.5	2	86.8	22.5	2.1	203	0.25	–
dw19	7.15	7.76	824	−44	11.90	210	112.6	33.6	89.6	5.7	68.6	21.7	–	174	0.154	–
dw21	7.03	8.03	776	−50	11.01	350	140	34	74.6	16.7	88.1	21.6	–	56.9	0.157	–
dw22	6.95	7.99	827	−73	10.91	320	149	38.5	37.8	13.1	55	24.7	–	57.6	1.054	–
dw26	7.02	7.94	1344	−74	9.85	370	125.6	64.2	124.3	3	155.3	66.5	–	264.4	0.411	0.01
dw27	7.31	8.32	1193	−45	10.64	280	116.5	59.1	122.2	10.2	110.0	88.5	–	180.6	0.422	0.01
CUL	7.07	7.07	782	−3	9.66	276	101	42.3	60.2	2.9	80.2	18.6	–	125.5	0.378	0.02

pH, electrical conductivity, *Eh* and temperature data are average values over the study period ($n > 30$). All values in mg L^{-1} except pH, alkalinity (mg L^{-1} as $CaCO_3$), electrical conductivity (μS cm^{-1}), *Eh* (mV) and temperature (°C). –, below detection.

[a]Locations: BH13b gives a close approximation of groundwater chemistry from the sump in the quarry void: the groundwater source for the quarry wetland. TJ, Thrislington Jane from which pumped water is also extracted for use in workings prior to discharge into the quarry wetland. OF1, Workings outfall in the quarry wetland. CUL, Culvert beneath railway connecting the reference site to the quarry wetland. Locations dw1–12 are located on the quarry wetland, locations dw13–27 are situated on the reference site.

9.0–9.3 at dw1–3, which is diluted with distance from the outfall through dw4 (pH 8.52) to more neutral levels in the west of the wetland (pH 7.3–8.0). This transition is a result of two factors: dilution with waters from the west of the railway and buffering by the organic-rich reed-bed substrate.

3.5. Nutrient availability and substrate characteristics

Table 2 presents a comparative display of major nutrient contents of substrate extracts from the reference site and quarry wetland. A clear pattern is the difference in calcium and magnesium concentrations between wetland cells, which is to be expected due to the presence of highly soluble CaO and MgO in the substrate around the outfall (derived from the calcination works). Calcium levels in sediment extracts were around four times greater in quarry outfall areas than in the reference sediments, whilst magnesium levels were roughly an order of magnitude greater in quarry samples than in reference site samples.

Clear differences in the organic content of the substrate were apparent between the vegetated substrate units (in both reference and quarry sites) and unvegetated quarry silts. The fen-peat deposits in the reference wetland had the highest values for LOI at around 49.5% by weight, slightly higher than levels to the north of the quarry wetland and in the reed-bed areas (mean: 31.9%) that have well-developed organic surface horizons overlying inorganic calcareous quarry sediment. Samples from areas of the unvegetated, recently deposited quarry sediment around the outfall show extremely low LOI values (mean: 4.18%) that reflect the largely inorganic nature of fines from the workings.

Nitrogen and phosphorus levels mirror the soil organic content in the manner in which they differ between high pH quarry outfall areas and organic-rich reference site samples. Both N and P availability were low in the organic-poor calcareous sediments around the quarry outfall, with extractable P being below detectable levels in three samples. Conversely, potassium levels were close to double the reference site values in sediments by the quarry outfall. This elevation is consistent with K-enrichment in the outfall effluent. Analysis of selected mineral micronutrients (Fe, Mn, Zn) showed no clear differences between levels in the reference site and of those in the quarry substrate.

Soil moisture condition may be a significant influence in sustaining plant communities in areas that are not perennially inundated, especially given the contrasting physical properties of the substrate between inorganic calcareous fines and organic-rich peat at the Thrislington site. Moisture values were fairly consistent within each of the two sample locations (uncolonised silt sands and vegetated fen/reed-bed) with an average moisture content by soil volume of 24% (S.E. ± 0.601, $n = 63$) in open calcareous quarry sediment. The moisture content rose to an average of 57% (S.E. ± 1.73, $n = 66$) in organic root mat areas to the north of the quarry site. This percentage change represents a shift in the ratio of soil matrix: moisture content from 1:1.326 to 1:0.333, i.e. a fourfold reduction in the relative content of moisture between the substrate types. However, although the absolute values of soil moisture differ, this does not indicate that available water to plants varies similarly, since this may depend on cohesive forces and pore size distribution in the substrate (A.J. Baird, personal communication, 2005).

4. Discussion

Increased winter flood flows and reduced base-flows in drier months downstream of quarry workings have previously been cited as potential hydrological implications of limestone extraction (Hobbs and Gunn, 1998; Thompson et al., 1998). The data presented here provide quantitative evidence to support such trends, but of greater importance are the subsequent impacts of exacerbated regime on vegetation patterns. Field observations showed the exacerbated drawdown in the summer months to lead to dehydration and desiccation of some plant species around the wetland margins (e.g. *Hippuris vulgaris, Equisetum palustre*). However, the extent of such impact did appear to be relatively isolated, with the dominant *Typha latifolia* and *Phragmites australis* persisting across much of the quarry wetland even in the prolonged dry periods experienced during summer 2001. The largely peripheral importance of rapid sedimentation in the quarry wetland suggests that the physico-chemical environment imposed by the high pH workings effluent and the fluctuating water levels are the main (potentially interacting) influences on low vegetation diversity across the quarry wetland.

Calcareous high pH conditions, such as those encountered in the quarry wetland where pH > 9.5 in surface horizons, are generally considered limiting to plant growth due to a range of direct and indirect changes in nutrient cycling. High pH of this nature is typically associated with the hydration of lime (CaO); at Thrislington this source is related to the calcination operations in the processing plant. The wetland source water, and to a lesser extent run-off within the processing plant site, come into contact with lime or dolomitic quicklime (CaMgO, but predominantly a complex of CaO and MgO), before discharge in the form of spoil heaps where lime kiln slag is deposited. The hydration of lime to form slaked lime (calcium hydroxide) liberates the hydroxyl ion (OH^-) to solution, thereby creating high pH conditions. Although OH^- abundance can directly induce toxicity in some plant species (Bradshaw and Chadwick, 1980; Rowell, 1988),

Table 2
Nutrient availability in wetland substrate between the reference site, outfall areas and vegetated areas of the quarry wetland (all mg L^{-1} except pH and LOI)

Location	pH	LOI (%)	N	P	K	Ca	Mg	Fe	Mn	Zn
Quarry outfall	9.38 (±0.16)	4.18 (±0.62)	0.841 (±0.303)	0.177 (±0.064)	43.2 (±9.6)	2039 (±132)	492 (±116)	0.45 (±0.12)	0.64 (±0.08)	0.004 (±0.0005)
Quarry vegetated	7.95 (±0.05)	31.9 (±0.62)	2.27 (±0.413)	0.459 (±0.084)	32.9 (±15.3)	1774 (±268)	307 (±106)	0.511 (±0.22)	0.70 (±0.12)	0.002 (±0.0002)
Reference site	7.42 (±0.06)	49.5 (±1.81)	2.34 (±0.199)	0.437 (±0.026)	26.6 (±7.5)	455 (±153)	43.6 (±13.1)	0.656 (±0.15)	0.31 (±0.09)	0.012 (±0.002)

Standard error of mean in parentheses, $n=6$ for quarry outfall, 7 for quarry vegetated and 7 for reference site. LOI, loss on ignition.

the principal constraints to growth under high pH conditions are related to reduced P availability (as a result of co-precipitation with Ca and Mg to form insoluble complexes; Patrick and Khalid, 1974), reduced K availability (Gemmell, 1977; Kinzel, 1983) and reduced solubility of many essential micronutrients, particularly Fe, Mn, B, Zn and Cu. At Thrislington, reduced P and N availability were clearly apparent in the quarry wetland substrate relative to organic-rich areas (in contrast, K availability was higher). High pH and elevated Ca levels in waters and substrate were coincident with low extractable P; it is difficult to infer causality however, without detailed geochemical testing. The correlation between organic content of the substrate and extractable P (R^2 of 0.56, $n=20$) does, however, suggest the importance of organic sources for P in surface horizons.

Assessment of the distribution of plant species in the quarry wetland suggests that only a minority of plant species can occupy areas of high pH, organic-poor, calcareous quarry sediment with fluctuating water levels. Species seen to proliferate in these localities tend to be robust, clonal dominants such as *Phragmites australis,* and *Typha latifolia* in wetter areas. These species are widely documented as being tolerant of a range of pH conditions (e.g. Haslam, 1972; Rivard and Woodard, 1989). In drier areas (with water tables around 41–50 cm below ground surface) common species include those indicative of alkaline environments (e.g. the calcicole moss *Ambylstegium riparium*) or ruderal species (e.g. *Agrostis stolonifera, Chamaenerion angustifolium, Senecio jacobea, Tussilago farfara*). These latter taxa have been shown from other studies to be common early colonisers in the similar dry calcareous environment of disused Magnesian and Carboniferous limestone quarry floors (e.g. Bradshaw and Chadwick, 1980; Hodgson, 1982).

Nutrient-poor conditions in the quarry-borne silt-sands were found to be coincident with poor moisture retention characteristics and low organic content in areas close to the outfall that were only seasonally inundated. Although the four-fold reduction in the soil moisture content of surface horizons of quarry sediment relative to organic-rich horizons elsewhere at the site offers no indication of actual water available to plants, this difference was coincident with the rapid shift in vegetation assemblage from moisture-demanding taxa such as *Phragmites australis* and *Typha latifolia* to the ruderal communities described above. These latter communities appear tolerant of the nutrient-poor, high pH conditions. This gradient appears to by-pass the water-line sedge and herbaceous communities abundant both on the adjacent reference site and in littoral areas of quarry ponds where high pH, nutrient-poor sediments are not characteristic.

4.1. Restoration and management implications

Wetland creation as a consequence of mineral extraction has been previously documented by Nawrot and Klimstra (1989) and Atkinson and Cairns (1994). The former describe colonisation of hydrophyte taxa in settling ponds associated with surface mining activity and emphasise the unique opportunity for wetland habitat creation when lagoon structures are suitably designed. This opportunity is echoed by Atkinson and Cairns (1994) who describe spontaneous wetland establishment in settling ponds with results showing a considerable species diversity akin to 'natural' wetland sites. At Thrislington, spontaneous succession within the quarry wetland has taken place over approximately 30 years. This unmanaged process has resulted in species-poor *Typha latifolia* and *Phragmites australis* reed-bed-dominated assemblages persisting over a wide range of moisture conditions in the quarry wetland. These taxa are robust and tolerant of the initial high pH substrate and wide amplitude moisture conditions imposed by quarry pumping operations. Although this spontaneous succession within the quarry wetland does not yield as diverse an assemblage as in the adjacent reference site, the process can still be viewed as beneficial from the point of view of wider conservation drivers (e.g. EU Habitats Directive 92/43/EEC) aimed at increasing the amount of this habitat type across the UK. The development of the reed-bed habitat in the quarry wetland also appears to be of significance in buffering the high pH influent waters and ameliorating high sulphate loadings (Mayes, 2003). Research is currently ongoing to detail the scope for utilising wetlands to ameliorate high pH.

Should recovery of wetland habitat akin to the relatively undisturbed condition of the adjacent reference site be desired, then manipulation of the recovery process is likely to be required. Prach et al. (2001) document protocols for using spontaneous vegetation succession in ecosystem restoration, including prediction of successional development and monitoring of results. It may also be possible at Thrislington to influence successional development by techniques such as application of organic mulches over high pH calcareous media. This approach has been previously documented to foster development of rich rendzina soils and promote revegetation (Bradshaw and Chadwick, 1980). Organic mulches serve to overcome nutrient availability constraints and improve moisture retention, but the application of this restoration technique up to now has been largely confined to dry skeletal surfaces associated with extractive industries (e.g. Roberts and Bradshaw, 1985; Vetterlein et al., 1999), rather than settling lagoons with potential for wetland development. Another approach, the introduction of suitable native species to accelerate the colonisation process, has been detailed by Ash et al. (1994) for both raised alkaline Leblanc waste (surface pH 1–9) and blast furnace slag (surface pH 1–8) in NW England, and may be of benefit on the quarry wetland cell at this site.

5. Conclusions

The hydrological, hydrochemical and floristic impact of pumped groundwater on a wetland area at Thrislington Quarry, County Durham has been examined in a coupled wetland study. Monodominance of *Phragmites australis* and *Typha latifolia* reed-bed was apparent across a wide range of conditions in a quarry wetland, in contrast to a relatively diverse gradation of communities along a moisture gradient in an adjacent reference site. These differing community transitions were highlighted using DCA and through application of revised Ellenberg *F*-values. Areas of rapid sedimentation (up to 8.2 cm yr^{-1}) were of peripheral importance in limiting the establishment of a diverse range of species in the quarry wetland. The principal influence on low species diversity appears to be related to the physico-chemical environment created by the workings effluent. Exacerbated drawdown and a fluctuating hydrological regime were coincident with elevated pH (up to 12.8) and a high sediment load. This created a nutrient-poor calcareous substrate in the quarry wetland that constrained colonisation of a varied flora such as that present in the adjacent reference site. Poor moisture retention in the quarry-derived sediments provided further edaphic constraints to plant growth and favoured proliferation of ruderal taxa when sites were not inundated.

Although spontaneous recovery of the quarry wetland has not given rise to plant communities as diverse as those on the adjacent reference site, the development of reed-bed habitat is of benefit for habitat creation and local biodiversity, and also in improving water quality of the workings effluent. As such, the status of wetland habitat within limestone extraction workings can be enhanced through suitable design of lagoon structures and careful management of the recovery process, possibly including directed vegetation succession. Further research is, however, still needed on the possible hydrochemical benefits of wetlands on quarry effluents and on methods for accelerating the colonisation of suitable wetland taxa on skeletal lagoon substrates.

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