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# Groundwater–surface water interactions at a fen margin: hydrological controls on the micro-habitat of an indicator snail species *Vertigo geyeri*

**ANNA KUCZYŃSKA, PAUL JOHNSTON & BRUCE MISSTEAR**
*Trinity College Dublin, Department of Civil, Structural and Environmental Engineering, Museum Building, Dublin 2, Ireland*
bmisster@tcd.ie

**Abstract** Pollardstown fen is an important groundwater-dependent ecosystem in eastern Ireland. One of the ecological features of the fen is the rare snail species *Vertigo geyeri*, which is protected under the European Union Habitats Directive. A major study in the period 2002–2005 focused on establishing the micro-meteorological and micro-hydrological requirements for this indicator snail species at Pollardstown fen. It was shown that high relative humidity (above 80%) and close proximity to a phreatic water surface (approximately 0.1 m below ground surface) are important for maintaining snail populations. A study of the groundwater inflows to the fen, involving measurements of vertical and lateral hydraulic gradients, coupled with an evaluation of soil thermodynamics and meteorological observations, suggested that the hydrological regime of the fen is sensitive to both the groundwater inflow rate and the transpiration process of the wetland vegetation. Local topography and geomorphology are important considerations when deciding on the extent of potential snail conservation areas, as the long-term viability of conservation sites is likely to be greater in areas with gentle slopes that allow seepages to emerge at lower levels, if such seepages are reduced or lost at higher elevations.

**Key words** fen; wetland; eco-hydrology; hydro-ecology; *Vertigo geyeri*; bioindicators

## INTRODUCTION

The introduction of the Water Framework Directive in Europe (European Commission, 2000) has focused attention on the linkages between surface water, groundwater and groundwater-dependent terrestrial ecosystems. Pollardstown fen is one of the most important wetland sites in Ireland. It is home to many species of birds and flora, and has a diverse population of invertebrates, including the rare species of snail, *Vertigo geyeri*. This snail is a protected species under the European Habitats Directive (European Commission, 1992). The snail is very small in size (up to 2 mm), has limited mobility and requires relatively stable micro-habitat conditions. It thus serves as a sensitive indicator species for fen conservation.

The ecology of the fen and its relationship with the surrounding aquifer was studied in detail between 2002 and 2005. The impetus for the study was the construction of a major road in a cutting below the water table in the local sand and gravel aquifer, and the concern that dewatering operations might lead to a decline in water levels and hence a reduction in spring flows to the fen, with consequent impacts on the fen ecology, including the sensitive *V. geyeri* snail.

This paper addresses the snail's micro-habitat, which was studied at a total of four sites around the fen margin, and then describes the relationship between the fen micro-habitat, micro-hydrology and the regional hydrogeology. This relationship was observed at one particular site, known as Site A, which was the closest to the new road layout and hence potentially the most sensitive to the dewatering activities.

## HYDROGEOLOGY

### Regional setting

Pollardstown fen is located within the Curragh sand and gravel aquifer, about 40 km west of Dublin (Fig. 1). The fen formed in a clay and peat filled depression, about 2.2 km$^2$ in area, which lies within the northern part of the Curragh aquifer. Inflows to the fen occur via a series of

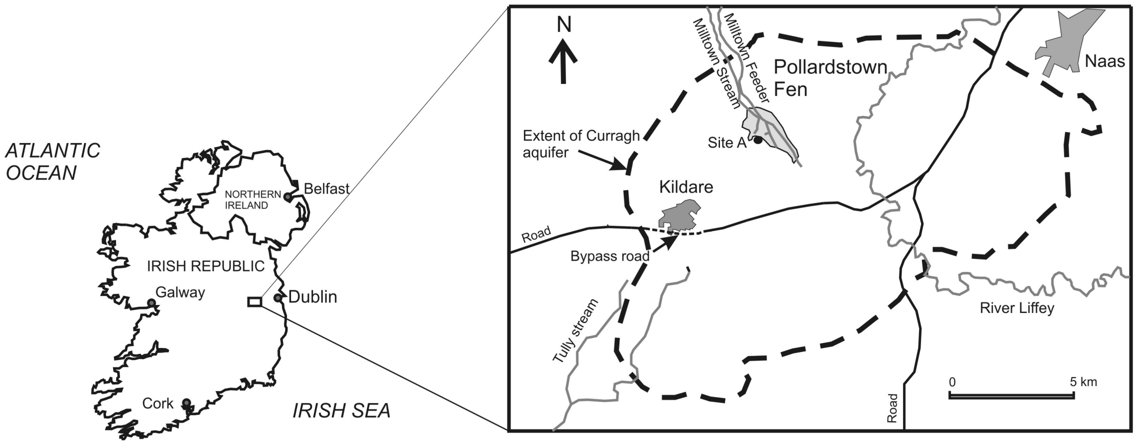


**Fig. 1** Location of Pollardstown fen and approximate extent of the Curragh aquifer.

seepages and springs mainly located around the margins of the fen. The main point of discharge from the fen is the Milltown Feeder canal, which flows to the north.

The glaciofluvial sands and gravels of the Curragh aquifer were deposited in a trough in the underlying Carboniferous limestone bedrock during the Quaternary period. The deposits attain thicknesses of over 60 m in the centre of the trough, but they are typically between 20 and 40 m in thickness elsewhere. These deposits display appreciable variations laterally, and often include clayey or silty horizons. In places, the sands and gravels are capped by a thin (less than 3 m) layer of boulder clay.

Given the variable nature of the fluvioglacial deposits, the aquifer properties are also highly variable: estimates of hydraulic conductivity range from less than 0.1 m/day where the gravels are clayey, to 200 m/day where the sands and gravels are well sorted (see Misstear *et al*., 2008, for a summary of aquifer test data); the clays underlying the fen have a hydraulic conductivity of less than 0.001 m/day (Daly, 1981). In a study of groundwater recharge, an analysis of groundwater level hydrographs suggested an average specific yield for the Curragh aquifer of around 0.19 (Misstear *et al*., 2008).

The aquifer is generally unconfined, although confined conditions may arise locally where clay or other low permeability layers are present, notably at the fen margin where the snail populations occur (see conceptual model of the upward seepage mechanism at the fen margin given later in the paper). Depths to groundwater vary from a maximum of over 20 m in some central parts of the aquifer (where there is a groundwater divide) to zero at locations of groundwater discharge, including the springs and seepages at Pollardstown fen. The corresponding range of groundwater elevations (above Ordnance Datum) is from approximately 92–93 m OD at the groundwater divide to 88–89 m OD at the fen margin, which gives a driving head to the fen margin of approximately 4 m. Seasonal fluctuations in groundwater level in the Curragh aquifer are typically between 0.5 m and 2.5 m, with the smaller fluctuations occurring closer to the discharge zones.

## Hydrogeology at the fen margin

At the fen margin, phreatic water levels in the fen peat (which are higher than the surface water levels in the main fen) are influenced by upward seepage from the underlying gravel aquifer. As there is a significant driving head in the regional gravels, the rate of seepage is essentially controlled by the relative elevation of the site and also by the hydraulic resistance offered by the overlying layers of clay and peat – upward seepage rates are possible only where the clay is thin or absent.

The simplified conceptual model of the seepage delivery at the fen margin used in this study assumes that there are two layers of different permeabilities (hydraulic conductivities), in which the upper one is much less permeable and acts as a confining layer for the lower, higher permeability layer (Fig. 2). The upper layer consists of 0.5–1.0 m thick peat and the lower one comprises an extensive gravel aquifer. This confining layer of peat results in artesian heads in the gravels and causes upward vertical flow whenever the driving head is sufficient. The upward seepage rate (measured here as specific discharge or Darcy velocity) is controlled by three variables: (a) permeability (hydraulic conductivity) of the material in the vertical profile through which the water movement occurs; this is the mean vertical permeability of each geological layer within the profile; (b) hydraulic head of water in the confined gravel layer; and (c) evapotranspiration rate at the surface. Saturation of the acrotelm (upper peat) is sustained whenever the quantity of water supplied to that layer is delivered at a rate higher than the evapotranspiration rate, i.e. when:

$$AE \leq q_z \tag{1}$$

where AE is the actual evapotranspiration at the fen surface (m/day) and $q_z$ is the upward seepage rate (m/day).

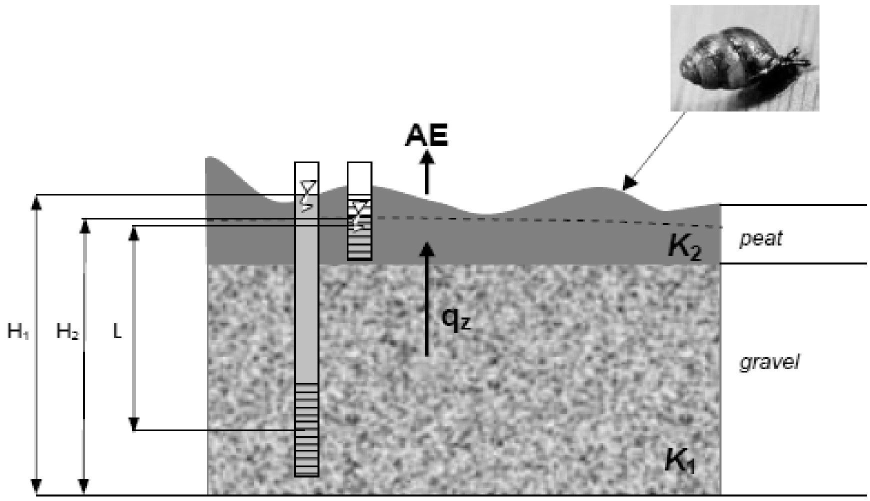


**Fig. 2** Simplified conceptual model of the upward seepage zone at the fen margin (where the fen peat directly overlies the gravel aquifer). $H_1$ is the water level (head) in the gravels under the fen (m); $H_2$ is the water level (head) in the peat (m); L is the distance between screens in the deep and shallow piezometers (m); $K_1$ is the permeability (hydraulic conductivity) of gravel (m/s); $K_2$ is the permeability of peat (m/s); and $q_z$ is the upward seepage rate (m/s).

## RESEARCH METHODOLOGY

The research methodology involved two main tasks, which arose from the overall aim of protecting the snail species *V. geyeri.* Firstly, the characteristics of the micro-habitat required by the snail were investigated at four locations around the fen margin, and secondly, the relationship between the snail micro-habitat and the regional hydrogeology was investigated in detail at one site on the southern fen margin, known as Site A (Fig. 1). The fieldwork was conducted between 2002 and 2005.

### Snail micro-habitat and the micro-hydrological regime

Detailed observations of the snail micro-habitat were made within four areas located around the fen margin. The observations focused on the micro-meteorological regime in areas where the *V. geyeri* snail was known to occur and included observations of air humidity, air temperature, soil temperature and incoming radiation at the fen surface. All parameters were recorded using automatic data loggers with a one-hourly logging frequency; the data were later analysed at daily, monthly and seasonal time scales. The peat soils were examined for soil moisture (field), surface wetness and soil water content (laboratory). Soil moisture was measured in the field using gypsum blocks (0.02 m in diameter and 0.03 m in depth), which were placed in peat in the direct vicinity of known snail locations. Soil moisture measurements were taken using a soil moisture meter with a range of 1–100%, with 100% indicating full saturation. Surface wetness was measured by small clay balls designed specifically for this study. The clay balls were made of Hortag clay material, which is half of the weight of sand and gravel and can absorb up to 30% of its own weight in water. The clay balls were used to mimic snails and to measure the "moisture stress" that a snail is likely to experience under dry conditions. The clay balls, which were 0.005 m diameter, were placed on the peat surface, between moss leaves and debris on which the snail tends to rest. The experiment involved measurements of the change in weight of small clay balls after exposing them to different surface wetness conditions. The absorption characteristics of clay allowed changing saturation conditions to be measured within the plant cover at ground level using an approach analogous to the moisture content concept given by British Standards Institution BS 1377 (1990). In addition, the soil water content of peat samples (collected from locations where snails had been found) was determined in the laboratory using an oven drying method (Maciak & Liwski, 1996).

The snail's micro-hydrological regime was established from water level observations adjacent to the known snail locations. The snail can relocate within small areas with respect to water availability. The proximity of the water table to the ground surface and the spatial distribution of snails with reference to surface water contours were therefore considered to be potentially good indicators of acceptable hydrological conditions. Observations were made using pressure transducers which were installed in 0.05 m diameter perforated plastic pipes pushed into the surface peat layer, 0.5 m below the ground surface; the transducers were set to log water levels every hour. Average daily water level was then compared against the snail presence at the site.

The presence of the snail was established by monthly snail surveys carried out within five Vertigo Quadrats that were 0.5 × 0.5 m in size, with a 0.05 m sub-grid within each quadrat. These surveys were undertaken by a specialist ecologist, Dr Evelyn Moorkens, and are reported in WYG (2004). The topography of these quadrats was surveyed using GPS equipment with an accuracy of 0.02 m on the vertical axis, and maps for each Vertigo Quadrat were drawn using Surfer 7 software. Daily average water level contours and the locations of snail sightings (for a given day when the snail survey was carried out) were added to the topographical maps. The proximity of the snail to water in both the vertical and horizontal directions was established using topographic maps and by calculating vertical distances between topographic and observed water level elevations. The snail counts were repeated every month over each summer between 2002 and 2005. In total, 69 records exist for the presence of *V. geyeri*, with the corresponding water level. Since the focus of the study was on the snail habitat, only positive snail counts were analysed for proximity of the water table to the ground surface.

### Relationship between the fen hydroecology and the surrounding aquifer

The relationship between the hydrology and hydroecology of the fen margin and the regional hydrogeology was established from groundwater observations in the Curragh gravel aquifer and in the peat layer at the fen surface. This was studied in detail at one site (Site A), approximately 400 m$^2$ in size, located at the southern fen margin, where groundwater from the regional sand and gravel aquifer seeps into the fen. Nine nests of piezometers were drilled at this site, targeting three depths: shallow (2–5 m) and deep (7–9 m) piezometers in the sand and gravel aquifer underlying the fen, and shallow piezometers in the fen peat (1 m deep; WYG, 2002). The locations of the study site and the relevant groundwater monitoring locations are shown in Fig. 3.

Two approaches were used to investigate the delicate water balance between upward seepage rate and evapotranspiration: a Darcian approach and a thermodynamics approach:

**(1) Darcian approach** The upward seepage rate (expressed as specific discharge) $q_z$, was calculated using Darcy's law. Water level data were available on a bi-weekly basis and were collected in piezometers SP31 (in gravels beneath the fen, representing the Curragh aquifer) and S10 (peat layer, Fig. 3). The hydraulic conductivity of each stratum was established through *in situ* testing (Kuczyńska, 2008), and from a review of previous reports on

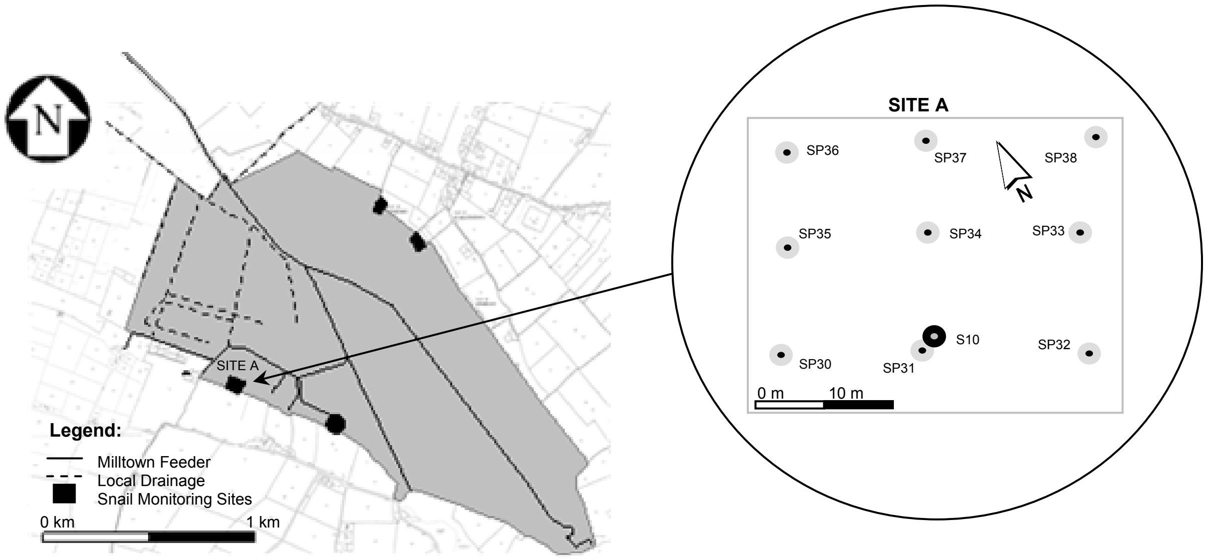


**Fig. 3** Location of Site A at Pollardstown fen, including piezometers within site A.

Pollardstown fen (Daly, 1981; Hayes *et al*., 2001). Potential evapotranspiration (PE) was calculated using a modified Penman-Monteith equation (Allen *et al*., 1998) and was based on climatic data from a weather station installed on the fen. Daily actual evapotranspiration (AE) was computed using daily rainfall data collected at the fen and the fen PE data, applying suitable crop coefficients for the fen vegetation. The *net* upward seepage rate was calculated by deducting actual evapotranspiration from the seepage rate (specific discharge). These *net* seepage rates were then compared with fluctuations in water levels within the phreatic zone in the peat layer.

**(2) Thermodynamic approach** Vertical seepage rates, $q_z$, were also evaluated using thermodynamic profiles. The method is based on a convective heat transport model. Developed by van Wirdum (1991, 1998), the methodology involves measurements of the temperature at different depths of soil along a vertical axis. The model assumes that the temperature of soil at infinite depth is constant, and that it fluctuates at the soil surface where it is under the influence of ambient conditions. The temperature of soil at some intermediate depth reflects the fluctuations at the surface with decreased amplitude and a phase lag. When the thermal parameters of the soil medium are known, and when they are nearly equal to those of water, the gross velocity of the vertical flow of water can be estimated from the difference between apparent and real thermal diffusivities (van Wirdum, 1991). Analysis of temperature at different depths enables thermal properties of the soil in terms of thermal conductance and diffusivity to be determined, which are then used in estimating vertical seepage rates of water.

## RESULTS AND DISCUSSION

### Snail micro-habitat and the micro-hydrological regime

Micro-meteorology was found to be uniform across the whole fen. No major differences were found between data from the fen surface and the weather station. The only exception was that incoming radiation was about 50% less under the vegetation canopy at the fen surface compared to that at the weather station (where the instruments were above the fen vegetation). Surprisingly, humidity did not change much across the fen compared to the weather station data, but remained above 80% nearly all year round, with increased values in winter months. Two distinct periods can be distinguished during which meteorological parameters differ. Meteorological variability is at its lowest during the winter period, from November until February. These stable conditions are characterised by small diurnal fluctuations for all parameters, with humidity ranging between 65–95% and a daily average above 90%. Average air temperature is below 10°C in this period, but temperatures as low as –9°C were also recorded. Soil temperature is at its lowest in these months, with a minimum occurring in the middle of February; however, the soil temperature never fell below zero degrees. As expected, solar radiation is significantly less during winter than summer. In the spring and summer period, March to October, all parameters increased, both in value and in the extent of their diurnal fluctuations, with maximum values occurring in July. June to August were the hottest months, with average daily temperatures reaching 20°C. Increased air temperatures affected the temperature of the soil, but the highest soil temperature values were recorded in August, two months after the highest air temperature. The summer soil temperature ranged between 10 and 15°C. Humidity is the only parameter measured that decreased during the summer although, despite large daily fluctuations, the average level remained above 80%.

Soil conditions were found to be an important factor in the snail habitat in all parts of the fen investigated. Measurements of soil moisture (field), surface wetness and soil water content (laboratory) showed very high levels of saturation of the soil. The laboratory measurements of soil water content ranged between 66 and 81%, and the field soil moisture readings using gypsum blocks ranged between 83 and 94% with an average of 89%. High soil moisture has a direct effect on surface wetness conditions. The experiment using clay balls showed that fen surface wetness ranged between 52 and 100%; however, 69% of samples showed wetness levels above 80%. The shading provided by vegetation greatly affected the surface wetness level.

The overall fluctuation in the phreatic water level in the peat layer varied from 0.05 to 0.3 m below ground level (bgl) over the summer observation period (May to October 2002–2005). The range of fluctuations is controlled by the minimum water table level that, in turn, depends on the amount of groundwater that is supplied to the fen surface through groundwater seepage. Lower minimum water levels imply a deeper unsaturated zone, which can quickly become fully saturated after intensive rainfall, resulting in relatively high water level changes over short periods.

Comparison between the snail occurrence and elevation of the phreatic water table demonstrated that the snail was only found when the water table fluctuated between 0 and 0.2 m bgl, and where the average summer water level was no deeper than about 0.1 m bgl. On a horizontal scale, the snails seemed to occur within approximately 0.2 m lateral distance of standing water (Fig. 4.).

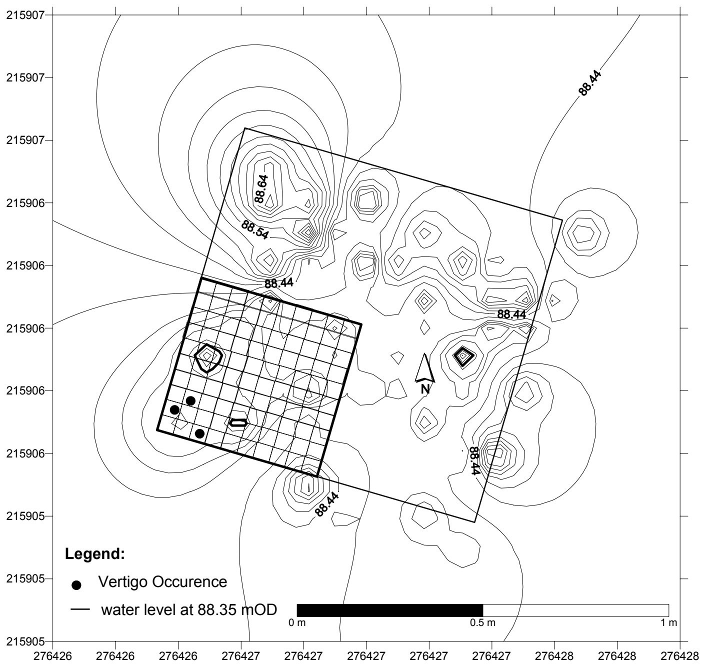


**Fig. 4** Example of a water table contour map showing the occurrence of the *Vertigo geyeri* snail.

## Relationship between the fen hydroecology and the surrounding aquifer

The seepage rate, as determined between piezometers SP31 and S10, is plotted against the actual evapotranspiration rate in Fig. 5. Both parameters displayed strong seasonal variations. The fluctuations in seepage rates followed the same general pattern as the fluctuations in water levels in the gravel aquifer (as shown by the hydrograph for borehole SP31, Fig. 6). The highest seepage rates occurred at the end of a winter period, February–March, when water levels in gravels were at their highest, and the lowest occurred at the end of the summer, or in mid-autumn. In terms of evapotranspiration, the lowest values were recorded in winter and the highest in summer months. Over the four years of observation, there was an overall decreasing trend in the seepage rate, which is consistent with the observed decline in water levels in the underlying fen gravels. It is also apparent that evapotranspiration rates tend to exceed seepage rates during the summer months, and this has an effect on the stability of water level in the peat. The negative *net* seepage rates (corresponding to a period of "seepage deficit") result in a lowering of the phreatic surface (Fig. 6).

Figure 5 shows a significant fall in seepage rates between 2003 and 2005. The highest seepage rates were recorded during winters of 2001 and 2003, at 0.0048 and 0.004 m/day, respectively. In 2004 and 2005, on the other hand, seepage rates barely exceeded 0.002 m/day. In both 2002 and 2003, seepage rates remained above 0.002 m/day until the middle of September (with short temporal falls below 0.002 m/day in July). In 2004 and 2005, seepage rates of approximately 0.002 m/day continued only until the end of June and July, respectively, and by the end of the summer season (October) they had reduced to 0 m/day and 0.0007 m/day, respectively. Using the thermodynamic approach, the analysis of soil temperature gradients suggested vertical seepage rates of a similar order of magnitude.

The average actual daily evapotranspiration for the summer months May to October 2002–2005 are included in Table 1. In 2003 and 2004, the average summer daily actual evapotranspiration was higher than that in 2002 by 0.0003 m (0.3 mm) which, over the 6-summer-month period, amounted to a difference of about 0.055 m (a 13% increase in summer AE compared to 2002). In May to October 2005, total summer actual evapotranspiration was 0.445 m, approximately 7% higher than for the same period in 2002.

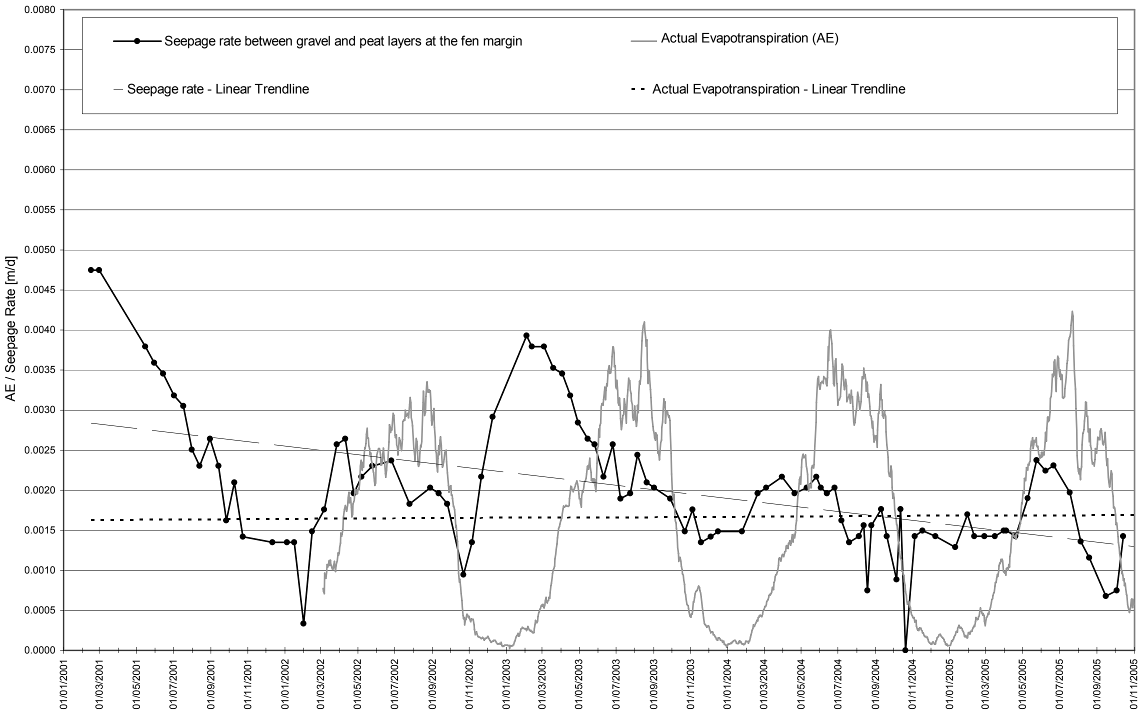


**Fig. 5** Distribution of seepage rate and evapotranspiration rate at the fen margin, Site A, Pollardstown fen, in the period 2001–2005.

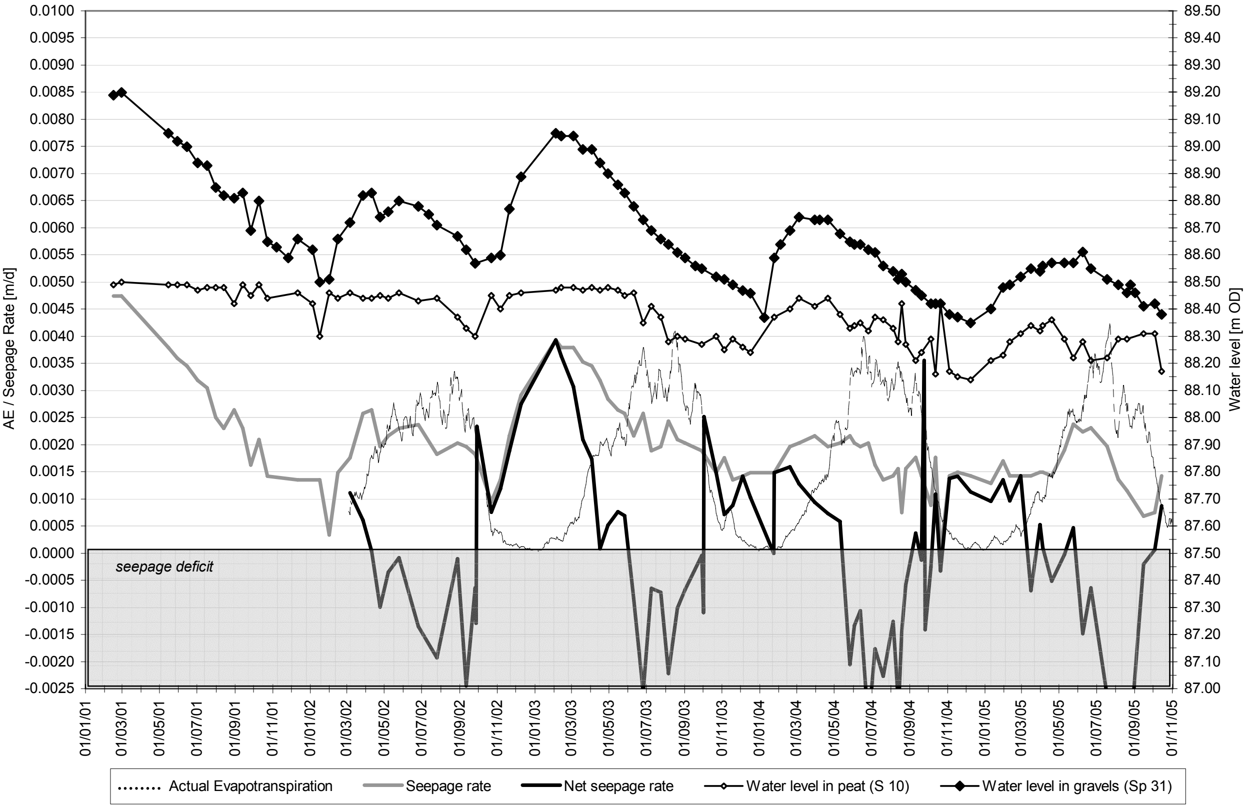


**Fig. 6** Variations in water levels, actual evapotranspiration and seepage rate, Site A, Pollardstown fen, 2002–2005. The *net* seepage rate is calculated by subtracting actual evapotranspiration from the upward seepage rate.

**Table 1** Summary of daily summer evapotranspiration and seepage rates (m/day), May–October 2002–2005.

| | | 2002 | 2003 | 2004 | 2005 |
|---|---|---|---|---|---|
| Summer seepage rate | Average (m/day) | 0.0019 | 0.0022 | 0.0015 | 0.0016 |
| | Total (m) | 0.0154 | 0.0238 | 0.0243 | 0.0162 |
| | Maximum (m/day) | 0.0024 | 0.0026 | 0.0022 | 0.0024 |
| | Minimum (m/day) | 0.0009 | 0.0015 | 0.0000 | 0.0007 |
| Summer potential evapotranspiration (PE) | Average (m/day) | 0.0019 | 0.0022 | 0.0022 | 0.0021 |
| | Total (m) | 0.353 | 0.403 | 0.410 | 0.383 |
| | Maximum (m/day) | 0.0045 | 0.0053 | 0.0067 | 0.0055 |
| | Minimum (m/day) | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Summer actual evapotranspiration (AE) | Average (m/day) | 0.0023 | 0.0026 | 0.0026 | 0.0024 |
| | Total (m) | 0.417 | 0.471 | 0.477 | 0.445 |
| | Maximum (m/day) | 0.0055 | 0.0061 | 0.0074 | 0.0065 |
| | Minimum (m/day) | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

**Table 2** Summary of vertical seepage rates and water levels in peat on the fen margin (Site A), May–October 2002–2005.

| | Water level in peat (S10) | | Seepage rate | | Net seepage rate | |
|---|---|---|---|---|---|---|
| | Average (m OD) | Range (m) | Average (m/day) | Range (m/day) | Average (m/day) | Range (m/day) |
| 2002 | 88.40 | 0.16 | 0.0019 | 0.0014 | –0.0005 | 0.0048 |
| 2003 | 88.36 | 0.20 | 0.0022 | 0.0012 | –0.0003 | 0.0051 |
| 2004 | 88.32 | 0.26 | 0.0015 | 0.0022 | –0.0008 | 0.0067 |
| 2005 | 88.26 | 0.14 | 0.0016 | 0.0017 | –0.0011 | 0.0049 |

The *net* seepage rates for the four summer periods are summarised in Table 2. Comparison with water level fluctuations in the peat (see Fig. 6 and Table 2) showed a negative *net* seepage (i.e. downward flow) occurring during summer months throughout the entire observation period 2002–2005. The overall negative gradient increased throughout the 2002–2005 period, which suggests that the groundwater delivery rate was not sufficient to sustain stable conditions and induced lowering of the phreatic level.

Comparison of the *net* seepage rate with the phreatic level (Fig. 6) shows that a "seepage deficit" leads to instability of the phreatic level whenever the net seepage rate is negative. Some seepage deficit, however, appears to be acceptable to the snail during summer months, provided that re-wetting takes place and the peat is returned to its field capacity during the winter months – as occurred, for example, in the summer of 2002 and the following winter of 2003. Analysis of hydrographs (Fig. 6) suggests that such re-wetting is necessary and requires significant seepage with rates probably not less than 0.004 m/day. When re-wetting at this rate did not occur (in the winters of 2004 and 2005), the phreatic level in the peat layer remained unstable during the winter and carried on in an unstable manner throughout the following summer. The observations suggest, therefore, that both summer and winter seepage rates need to be sustained at certain levels in order to maintain the hydrological conditions required by the *V. geyeri* snail. This in turn suggests that groundwater head in the underlying fen gravels must be sustained at, or above, a minimum level, in order to provide the required minimum seepage rate for stable phreatic conditions.

Applying Darcy's equation enabled this minimum groundwater head to be established for this particular study site. The mean permeability in the vertical profile at the fen margin was determined by *in situ* testing as $4.72 \times 10^{-7}$ m/s (Kuczyńska, 2008). Taking this permeability value, and also taking the average daily actual evapotranspiration in summer at 0.0025 m/day and the minimum water level in peat to be 0.2 m bgl (in piezometer S10), then the minimum hydraulic head in the underlying gravel layer is calculated to be 88.67 m OD (at piezometer SP31). This represents the groundwater head necessary at that location to drive the upward seepage flow in order to counter balance evaporative losses, keep the soil surface wet and the peat phreatic surface at the required stable level.

## CONCLUSIONS

This study investigated the preferred habitat of the rare species of *V. geyeri* snail in terms of micro-meteorology and micro-hydrology. The *V. geyeri* snail acted as a sensitive indicator of change for a particular fen margin environment.

It was found that the snail requires a consistently damp atmosphere with relative humidity varying between 80% and 95%, very small fluctuations in phreatic level (0–0.2 m), with the mean not more than 0.1 m below the ground surface, and soil moisture within the moss substrate at approximately 90%. The surface wetness level was found to be influenced greatly by shading vegetation.

Micro-meteorological conditions were found to be relatively uniform across the whole fen area, and it is thus concluded that micro-meteorology has less influence on the snail's occurrence than the micro-hydrological regime. Monitoring of phreatic water levels and snail populations over four summers suggested that the snail can tolerate fluctuations of between 0 and 0.2 m bgl and, furthermore, that the average summer water level should be within 0.1 m of the ground surface. In order to maintain this phreatic level at approximately 0.1 m bgl, groundwater needs to be delivered to the fen surface at rates that are at least equal to the average summer actual evapotranspiration losses from the surface, approximately 0.0025 m/day.

The links between the micro-hydrology at the fen margin and the regional hydrogeological regime were investigated through a quantitative analysis of vertical seepage rates (specific discharge) supplying water into the fen. This mechanism of seepage delivery depends on the layering of peat, clay and gravel at a particular site. As there is a significant driving head in the regional gravels, the rate of delivery (discharge) is controlled partly by the relative elevation of the site and partly by the hydraulic resistance offered by the peat and clay layers overlying the gravel aquifer.

At one particular monitoring borehole site (SP31, located at the southern fen margin), it was shown that in order to maintain stable water levels within the fluctuation range acceptable to the snail (0–0.2 m bgl), the hydraulic head in the underlying gravel layer should not fall below 88.67 m OD during the summer months, when the snail is most active. Maintenance of the summer water table above such a minimum threshold would restrict the water level fluctuation range, sustain surface wetness at a sufficiently moist level and also protect the snail from the possible risk of flooding after heavy rainfall events.

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