

# Three decades of water quality measurements from the Upper Severn experimental catchments at Plynlimon, Wales: an openly accessible data resource for research, modelling, environmental management and education

Colin Neal,<sup>1</sup>  
Brian Reynolds,<sup>2\*</sup>  
Dave Norris,<sup>2\*</sup>  
James W. Kirchner,<sup>3</sup>  
Margaret Neal,<sup>1</sup>  
Phil Rowland,<sup>4</sup>  
Heather Wickham,<sup>1</sup>  
Sarah Harman,<sup>1</sup>  
Linda Armstrong,<sup>1</sup>  
Darren Sleep,<sup>4</sup>  
Alan Lawlor,<sup>4</sup> Clive Woods,<sup>4</sup>  
Bronwen Williams,<sup>2</sup>  
Matt Fry,<sup>1</sup> Gwen Newton<sup>1</sup>  
and Dan Wright<sup>4</sup>

<sup>1</sup> Centre for Ecology and Hydrology, Crowmarsh Gifford, Wallingford, Oxon OX10 8BB, UK

<sup>2</sup> Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor Gwynedd LL57 2UW, UK

<sup>3</sup> Swiss Federal Research Institute WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

<sup>4</sup> Centre for Ecology and Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK

\*Correspondence to:

Brian Reynolds, Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor Gwynedd LL57 2UW, UK.  
E-mail: br@ceh.ac.uk

\*Correspondence to:

Dave Norris, Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Road, Bangor Gwynedd LL57 2UW, UK.  
E-mail: danor@ceh.ac.uk

## Introduction

Over the last 20–40 years major progress has been made in characterizing the hydrochemical functioning of catchments based on extensive, high-quality monitoring programmes. These data are vital for addressing issues, such as long-term responses of streams to external pressures, to assess the environmental impact. This is critical, for example, in relation to the issue of acidic deposition (Monteith and Evans, 2000; Monteith *et al.*, 2000; Evans *et al.*, 2001). Major long-term investment has been required in terms of personal commitment from scientists, science infrastructure and financial resources. It is now clear that such datasets need to be made available to the community to fully exploit this large public investment (Tromp-van Meerfeld *et al.*, 2008). For this to happen, materials and data need to be shared under the least restrictive terms within the context of a dedicated and sustainable commitment to public databases and repositories (Schofield *et al.*, 2009). Within our organization (CEH, Centre for Ecology and Hydrology) and its parent body (NERC, Natural Environment Research Council) major infrastructure investment is being made to develop a readily accessible data portal (the CEH Information Gateway: [gateway.ceh.ac.uk](http://gateway.ceh.ac.uk)) to make available the wealth of environmental information and data collected over several decades.

In this article, we flag newly available water quality data under this Gateway initiative. These data originate from extensive hydrochemical studies in remote upland catchments of the Upper River Severn draining the lower Palaeozoic Cambrian Mountains at Plynlimon in mid-Wales (Kirby *et al.*, 1997). The dataset comprises long-term data (in some cases, up to almost 30 years of weekly monitoring) on the chemical composition of rainfall, cloud water, stemflow, throughfall, stream water and groundwater, supported by detailed metadata describing sampling protocols, analytical methods and catchment characteristics. These data are of relevance to many areas of environmental science linked to issues such as atmospheric pollution, climate change, hydrological extremes, land use change and management. They are also of value for educational purposes such as data interrogation and environmental modelling. Within the CEH Information Gateway, other datasets provide freely available information such as meteorological/hydrological data (rainfall and river flows, rainfall distribution, wind speed, temperature, etc) and geomorphologic characteristics (elevation, soil and vegetation distribution maps) that may also be of value, for example in the context of modelling. This links with the goals of extending data linkages across the research fraternity within the context of the nascent NERC Pilot Virtual Observatory project ([www.environmentalvirtualobservatory.org](http://www.environmentalvirtualobservatory.org)).

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Raw data and data edited to remove likely errors are provided on the CEH Information Gateway, and it is for the user to make informed judgements concerning analysis and interpretation. For the future, a universal standard will need to be developed and applied in the context of changing methodologies, which determine detection limits and sensitivity. However, informed judgement can only come with the provision of raw data as it is impossible to go back to the original values once the data have been censored and subsequently stored. This article not only flags the database but also includes references to published work and comments on new findings. While we recognize the importance of making data as freely available as possible, this is performed in relation to the institutional copyright for the data and recognition of previously published work. These are critical performance indicators that give value and endorsement to ensure the long-term continuation of major environmental monitoring programmes. We point out the logistical challenge of bringing the information together. This is important to recognize the amount of time that may be needed. We urge ongoing and future research to put data management systems in place that are robust, requiring minimum retrospective modification to cope with the potential loss of

background knowledge that may occur when staff leave or research priorities change.

## Background

The headwater catchments of the adjacent River Severn (Afon Hafren) and River Wye (Afon Gwy) in the Plynlimon area of mid-Wales have been extensively studied for many years. Land use in the Wye catchment consists of semi-natural grassland, peat-land and improved grassland with sheep farming, whereas the Severn catchment supports plantation conifer forest (predominantly Sitka spruce—*Picea sitchensis*) in its lower half with semi-natural heath land and extensive deep peat in the headwater areas (Figure 1). The catchments are typical of large tracts of the UK uplands from about 400 to 700 m above sea level. The particular emphasis on forestry comes about because of the associated water quality and quantity issues linked to commercial plantation forestry rotation cycles. Extensive areas of the UK uplands were planted with conifer plantations between the First and Second World Wars in response to the strategic need for a sustained and secure timber resource (Hudson *et al.*, 1997a; Neal *et al.*, 1997a).

The geomorphology, land use, vegetation cover, soils, hydrology and sediment transport within the

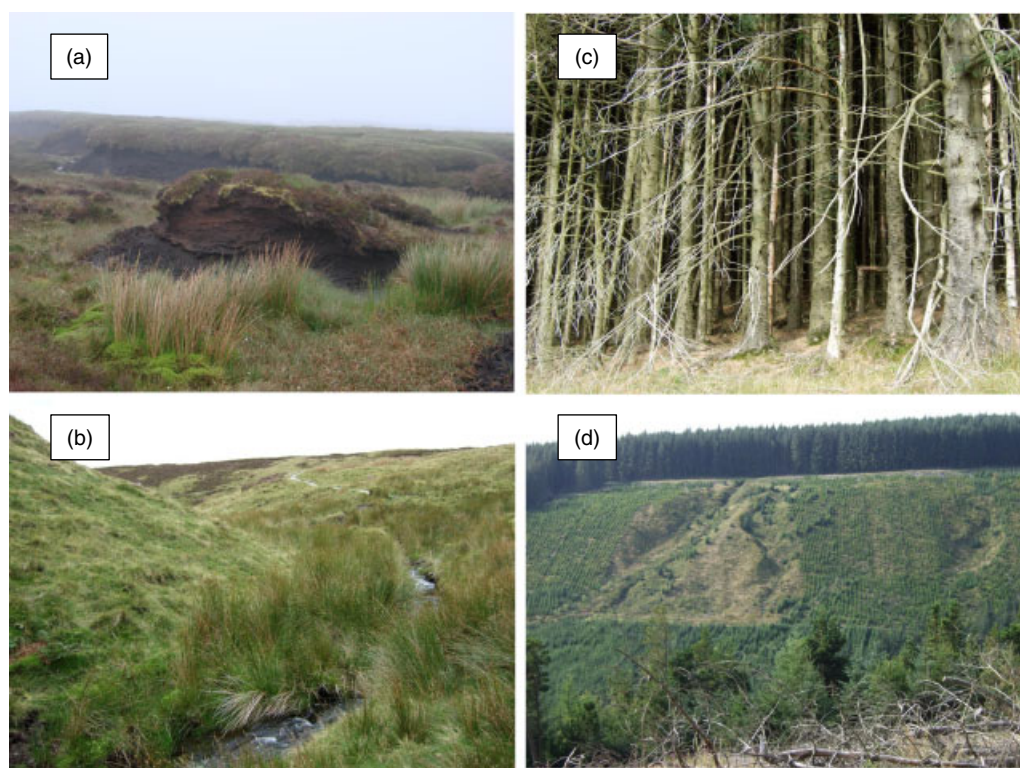


Figure 1. Photographs of the moorland and afforested parts of the Upper Severn catchment; (a) shows an eroding peat hag towards the top of the Afon Hafren catchment; (b) shows the Upper Hafren monitoring point approximately 1 km downstream of location in the photograph (a); (c) shows densely planted trees in the afforested area the Afon Hafren catchment and (d) shows a hill slope with standing forest on the skyline and a recently replanted area of clear-felled forest on the mid-slope. Note the large erosion gullies formed by scouring of forest drainage ditches on the steep slope

catchments have been described previously (Newson, 1976, 1985; Kirby *et al.*, 1991; Hudson *et al.*, 1997a,b; Brandt *et al.*, 2004) as have findings in relation to atmospheric deposition of pollutants, biogeochemical processes, land use change (Hornung *et al.*, 1985, 1986a,b; Reynolds *et al.*, 1988, 1992, 1997a,b) and plantation conifer forestry management (Reynolds *et al.*, 1986, 1988; Hudson *et al.*, 1997b; Neal *et al.*, 2004a,b,c).

### *The Upper Severn catchment*

*General catchment information.* The Upper River Severn has two main tributaries, the Afon Hafren and the Afon Hore. Between the two is a smaller tributary, the Nant Tanllwyth, which enters the Afon Hafren near its junction with the Afon Hore. Their respective catchment areas are 3.58, 3.17 and 0.916 km<sup>2</sup>. The upper parts of the Afon Hafren and the Afon Hore catchments are on hill top plateau dominated by blanket peat up to 2 m deep with seasonally saturated peat and gley soils in the valley bottoms. Podzol soils dominate the intermediate slopes in the lower parts of the Afon Hafren and Afon Hore catchments, whereas most of the Tanllwyth catchment is underlain by gley soils. The soils are acidic and typically less than 1 m thick with a low base saturation but high exchangeable aluminium content (Reynolds *et al.*, 1988) and the underlying bedrock comprises base-poor Ordovician to Silurian age mudstones, grits and shales. The lower parts of the Afon Hafren and Afon Hore as well as the entire Tanllwyth catchment were planted with conifers in several phases between the late 1940s and early 1960s (mainly Sitka spruce with some Norway spruce, Lodgepole pine and Larch). The trees were planted at 1.5 m spacing in rows. On wetter ground, the soils were ploughed before planting and a network of drainage ditches was created. The combined effect of the ploughing and ditching was to create very 'flashy' hydrograph responses to rainfall and enhanced rates of sediment transport (Newson, 1976; Newson and Leeks, 1987; Kirby *et al.*, 1991; Leeks and Marks, 1997; Marks and Rutt, 1997). Large areas of the catchments have now been felled.

The part of the Afon Hore catchment between the Upper and Lower Hore sampling points was clear-felled during 1985–1987 (Neal *et al.*, 1992a,b), and a small tributary of the Afon Hore (South 2 Hore) was also monitored (Neal *et al.*, 1994, 2003a). The catchment upstream of the Upper Hore site was clear-felled between 2006 and 2009. The Afon Hafren catchment has been thinned and progressively clear-felled in several phases over the last 25 years (Neal *et al.*, 2004a). For the Tanllwyth, the southern half of the catchment was clear-felled in 1996 (Neal *et al.*, 2004b). Apart from an area of high-altitude forest at the top of the Afon Hafren and Tanllwyth catchments,

all the clear-felled areas have been replanted with Sitka spruce. Comparative studies for brown-earth soils at Vyrnwy are discussed by Neal *et al.* (2004c).

*Monitoring programme.* Weekly monitoring began in May 1983 for a wide range of chemical constituents. The nature of the monitoring programme evolved over time to include rainfall, cloud water, stream water and groundwater (Table I) and to address the environmental response to the felling and replanting of conifers.

*Atmospheric inputs:* Rainfall chemistry was measured from the inception of the experiment, and cloud water was collected from 1990, at a site at the top of the Afon Hafren catchment (Wilkinson *et al.*, 1997). For a 2-year period, stemflow and throughfall were measured at a site near the Plynlimon field station (Neal *et al.*, 2003b).

*Main streams:* The Lower Hafren and Lower Hore were monitored from the start of the programme, the Lower Hafren providing a control for the Lower Hore clear-felling experiment. However, early results showed that the Lower Hore had a higher weathering rate as shown by higher calcium, pH and Gran alkalinity levels (Reynolds *et al.*, 1986). Consequently, monitoring commenced in 1984 in the Upper Hore to provide a better control for the Lower Hore. The Upper Hafren was monitored from 1990 to provide information on the chemistry of run-off from the moorland area at the top of the Afon Hafren catchment (Neal *et al.*, 2010). The Tanllwyth was monitored from 1991 to provide data for a completely forested catchment on gley soils (Neal *et al.*, 2004b). All the chemical sampling sites were located just upstream of flow gauging structures belonging to the CEH hydrological research network for the Plynlimon experimental catchments (Hudson *et al.*, 1997b).

*Small first order streams:* A small stream (South 2 Hore) was monitored before, during and after felling from 1988 to provide information on water quality changes for forest and harvested forest within a small catchment dominated by near surface inputs to characterize a 'soil' as opposed to a 'groundwater' end-member (Neal *et al.*, 2003a). Small (<5 ha) control and felling response sites were established in 1994 to provide more detailed soil end-member data for podzol and gley soils (South East 1 and South East 2 sites draining into the Afon Hafren and the Tan North, respectively, and Tan South sites into the Tanllwyth: Neal and Reynolds, 1999a,b).

*Groundwater:* Samples were collected across a network of boreholes from 1994 when it became clear from both soil water and stream water quality data

Table I. Summary information for the Upper Severn monitoring programme

Site	Area (ha)	Dominant soil types	Catchment or site land cover	Felling activity	Samples/year	Start date	End date	Approximate felling dates	Primary references
Atmospheric inputs									
Rainfall	—	Peat	Acid moorland	—	52	10 May 1983	Continuing	—	Wilkinson et al., 1997b
Cloud	—	Peat	Acid moorland	—	52	25 September 1990	Continuing	—	Wilkinson et al., 1997b
Throughfall	—	Podzol	Conifer plantation	N	52	06 February 1984	02 September 1991	Not felled	Neal et al., 2003b
Stemflow	—	Podzol	Conifer plantation	N	52	01 February 1984	02 September 1991	Not felled	Neal et al., 2003b
Main streams									
Upper Hafren	117	Peat	Acid moorland	—	52	17 July 1990	Continuing	—	Neal et al., 2010
Lower Hafren	347	Podzol/Gley	Conifer plantation	Y approximately 60%	52	10 May 1983	Continuing	1985 onwards	Neal et al., 2004a
Upper Hore	178	Podzol/Gley	Conifer plantation	Y 50%	52	28 August 1984	Continuing	2006–2009 March	Neal et al., 1997a
Lower Hore	335	Podzol/Gley	Conifer plantation	Y 50%	52	10 May 1983	Continuing	1985–October 1988	Neal et al., 1997a
Tanllwyth <sup>(a)</sup>	51	Gley	Conifer plantation	Y 50%	52	17 September 1991	04 May 1999	February 1996	Neal et al., 2004b
Tanllwyth Bridge	51	Gley	Conifer plantation	Y 50%	52	19 September 1995	Continuing	February 1996	Neal et al., 2004b
Small first order streams									
South 2 Hore	3–6	Podzol	Conifer plantation	Y 100%	52	19 April 1988	20 February 2001	August–October 89	Neal et al., 2003a
South East 1	2–4	Podzol	Conifer plantation	Y 100%	26	20 September 1994	14 February 2001	September–October 1995	Neal et al., 2004a
South East 3	2–4	Podzol	Conifer plantation	N	26	11 October 1994	27 April 1999	Unfelled control	Neal et al., 2004a
Tan North	<2	Gley	Conifer plantation	N	26	28 April 1994	27 April 1999	Unfelled control	Neal et al., 2004b
Tan South	<2	Gley	Conifer plantation	Y 100%	26	28 April 1994	14 February 2001	February 1996	Neal et al., 2004b
Groundwater									
South East 1 Borehole	—	Podzol	Conifer plantation	Y 100%	26	10 May 1995	27 April 1999	September–October 1995	Neal et al., 2004a
South East 3 Borehole	—	Podzol	Conifer plantation	N	26	10 May 1995	27 April 1999	Unfelled control	Neal et al., 2004a
Tannorth Borehole	—	Gley	Conifer plantation	N	26	09 August 1994	27 April 1999	Unfelled control	Neal et al., 2004b
Tansouth Borehole	—	Gley	Conifer plantation	Y 100%	26	05 July 1994	27 April 1999	February 96	Neal et al., 2004b
Upper Slope 1	—	Peat	Unplanted forest	—	12	24 April 1994	12 July 1995	—	Neal et al., 1997b
Upper Slope 2	—	Podzol	Conifer plantation	N	12	24 April 1994	14 June 1995	Not felled	Neal et al., 1997b
Upper Slope 3	—	Podzol	Conifer plantation	N	12	24 April 1994	12 July 1995	Not felled	Neal et al., 1997b
Lower Slope 1	—	Podzol	Conifer plantation	N	12	24 April 1994	12 July 1995	Not felled	Neal et al., 1997b
Lower Slope 2	—	Podzol	Conifer plantation	N	12	17 May 1994	12 July 1995	Not felled	Neal et al., 1997b
Lower Slope 3	—	Podzol	Conifer plantation	N	12	24 April 1994	12 July 1995	Not felled	Neal et al., 1997b
Lower Slope 4	—	Podzol	Conifer plantation	Y 100%	12/52	24 April 1994	14 February 2001	September–October 1995	Neal et al., 1997b, 2004a

Intermediate Slope 1	—	Podzol	Conifer plantation	N	12	24 April 1994	12 July 1995	Not felled	Neal et al., 1997b
Intermediate Slope 2	—	Podzol	Conifer plantation	N	12	24 April 1994	12 July 1995	Not felled	Neal et al., 1997b
Valley Bottom 1	—	Podzol/Gravel	Unplanted forest	—	12	24 April 1994	12 July 1995	—	Neal et al., 1997b
Quarry 1 Borehole	—	Podzol	Conifer plantation	N	26	05 August 1994	27 April 1999	Not felled	—

(a) The original sampling point on the Tanllwyth was affected by an influx of groundwater arising from a borehole introduced near to the river on 7 March 1995. Full monitoring continued at the Tanllwyth site until 4 May 1999 after which only pH and Gran alkalinity were recorded until 15 August 2006. A second sampling point called Tanllwyth Bridge was introduced on 19 September 1995, approximately 150 m upstream of the borehole.  
—denotes not applicable.

that baseflow could not simply be related to end-member inputs derived from the subsoil as previously believed (Reynolds *et al.*, 1988; Neal *et al.*, 1997b,c).

A schematic of the sample locations is shown in Figure 2.

*Sample pretreatment and chemical analysis.* Water quality measurements for each site comprise more than 50 analytes, including major ions, nutrients, trace elements, pH, alkalinity and conductivity. Water samples were filtered in the field through either 0.45 µm cellulose nitrate or glass fibre (GF/C) filters depending upon determinand. Unfiltered samples were collected in an airtight-glass bottle for pH, alkalinity and conductivity assay. To minimize sample deterioration before analysis, the samples were stored at 4 °C in the dark for analyses of metals, filtered samples were acidified to 1% v/v with high-purity-grade concentrated nitric acid.

The wide range of major, minor and trace element determinations required the use of a combination of electrometric, colorimetric, ion chromatography and inductively coupled optical-emission and mass spectrometry approaches. Over the lifetime of the study, the analyses have been variously undertaken at the CEH's laboratories at Plynlimon, Wallingford, Bangor and Lancaster. The methodologies used by the different laboratories are very similar and have been described previously (Neal *et al.*, 1997a). Extensive cross-checking was undertaken to ensure that the data from the various laboratories were consistent and compatible. However, over the years there were some methodological changes that meant that detection limits and sensitivities changed significantly in some cases; details of the changes are provided in metadata stored on the CEH Information Gateway. In general, analysis was usually undertaken in duplicate for all the assays apart from pH, Gran alkalinity and electrical conductivity that were analysed singly. International and internal CEH laboratory standards were used for calibrations, and intermediate standards provided a check for drift within each batch of samples. In most cases, the accuracy of the determinations was evaluated using materials supplied by the Aquacheck LGC Inter-laboratory Proficiency Testing Scheme.

*Collating the database: problems, temporary solutions and data enigmas.* To accurately document the changes that have occurred over the years, we have drawn upon meticulous record keeping in the form of field and laboratory forms/notebooks. The research started before the age of personal computers and easy-to-use digital data storage, so all of this information was on paper: huge masses of paper to be exact! An important task was to validate the transfer of the

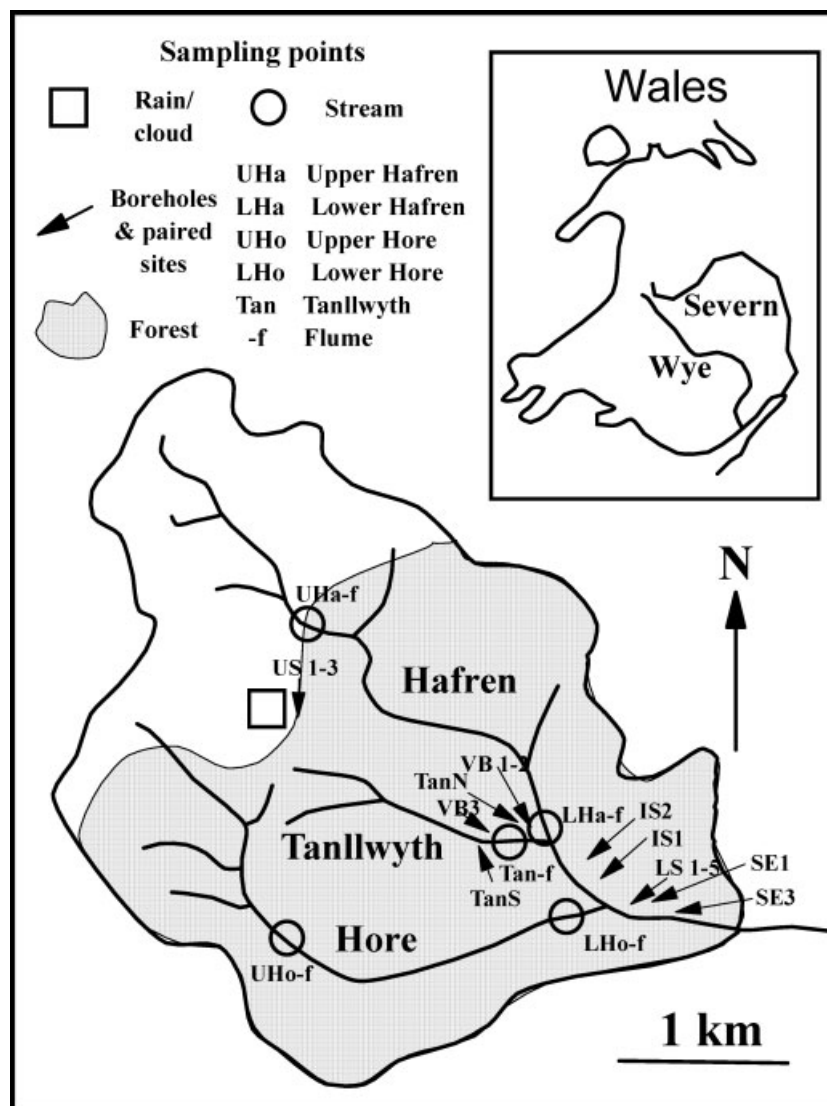


Figure 2. Outline map of sample site locations in the Upper Severn catchment at Plynlimon

key information from paper onto a database. For the water chemistry data, digital storage has been used in a variety of formats by different users and various CEH sites for around 15 years. Therefore, another important task was to consolidate the digital data into one agreed format in one single place. This needed to be performed now because principal investigators and laboratory managers were at or near to retirement and their acquired knowledge was needed to validate and make available all the background information.

Superimposed on this has been the need to have consistent names and units for analytical determinands. This may sound trivial but care has been needed with regards to the reporting of common determinands by different laboratories and laboratory staff. For example, the names nitrate and sulphate have been used by different laboratories even when the units might be different (e.g.  $\text{NO}_3$  or  $\text{NO}_3\text{-N}$ , mg/l), whereas for metals, concentrations have been

presented either in terms of mg/l or in terms of  $\mu\text{g/l}$  and sometimes they have been named differently (e.g. Ni, Ni(58), Ni(60)). Alkalinity has been particularly troublesome in relation to concept and units, where sometimes it has been considered in relation to bicarbonate concentrations where units of milligram per litre  $\text{CaCO}_3$  have been used, whereas at other times it has been linked to the total weak buffering components of acidity (Neal, 2001). For our studies, the latter definition is used with alkalinity being determined by a Gran titration procedure. It was also important to state that most of our measurements were for dissolved components, where the dissolved fraction is defined in most cases as that which passes through a  $0.45 \mu\text{m}$  membrane filter. In some cases, such as the trace metals, the dissolved fraction may include colloidal as well as truly dissolved components, while for the major and trace anions, ion chromatography or colorimetry may determine specific ions. Thus,

we have adopted an operational definition of 'dissolved'. The alternatives proved to be cumbersome, but the metadata informs the researcher as to what was actually determined. Within this commentary, acid neutralization capacity is calculated as the difference between the strong base cations ( $\text{Na} + \text{K} + \text{Mg} + \text{Ca}$ ) and the strong acid anions ( $\text{Cl} + \text{SO}_4 + \text{NO}_3$ ).

Although to many researchers these activities may seem trivial, they proved to be time consuming and the end product is a detailed metadata record that can be used by any researcher. All of this activity has been undertaken in the absence of an agreed international convention for reporting environmental analyses. Such a convention is urgently required. We point the reader to earlier work involving the development of a data determinand dictionary as part of a major UK initiative, the Land Ocean Interaction Study (Tindall and Moore, 1997).

Finally, for the reasons given above we have provided both raw data and data that have been edited for major outliers where we believe that the raw values are misleading because of transcription errors, sample contamination or other problems. Data editing requires balancing the risk of excluding values that are unusual but true (and therefore informative) and the risk of including values that are unusual and false (and therefore misleading); this delicate task cannot be accomplished blindly through algorithms alone but rather requires expert judgment. We have therefore exercised our judgment in the edited data, but we also provided the raw data so that users can see exactly what was done. In a few cases, we have excluded analytes entirely where the sensitivity has been particularly poor for a substantial part of the record.

We have not, however, routinely excluded values less than 0. Although real-world concentrations cannot be negative, individual measured values may be less than 0 when the true concentrations are small compared to the measurement uncertainties. Thus, negative values provide some indication of the instrument response to low concentrations at or near detection limit and to the potential for contamination of reagent blanks. For one determinand, Sb, the time series shows strong variations over time with gradual increases followed by a rapid decline and subsequent build-up. This does not seem to fit with hydrological or any other obvious change, but we cannot justify removing the data and it is for others to judge the worth. We recommend use of the edited data for consistency across users.

## Research Findings

### *General water quality issues*

There have been three overview publications over the years that describe the general water quality for the Upper Severn (Neal *et al.*, 1997a; Neal, 2000, 2004),

and there is little need to revisit these other than to highlight the main features, critical references and the more recent findings, particularly with regards to forestry rotation cycles and the felling of the upper part of the Hore catchment in 2007–2008.

*Water quality changes from the weekly to the decadal scale for moorland and minimally disturbed forested catchments. Atmospheric inputs:* Rainfall chemistry is highly variable reflecting medium to long-range transport of sea salt and pollutant components (Neal *et al.*, 1997a; Wilkinson *et al.*, 1997). Decadal variations also occur (Robson and Neal, 1996; Neal *et al.*, 1996, 2001) and for sea salt this links to the North Atlantic Oscillation (Evans *et al.*, 2001; Ness *et al.*, 2004). In terms of acidic deposition, sulphate levels have declined in rainfall and two critical measures of acidic deposition, alkalinity and acid neutralization capacity (ANC), have increased (Neal *et al.*, 2010).

Cloud water is volumetrically small in terms of water flux but highly enriched in many components and can significantly augment wet deposition of sea salts and many pollutant components, especially for the forested areas (Wilkinson *et al.*, 1997).

*Main and small first order streams:* Four types of behaviour are observed in the streams.

1. Major components with high variability in rainfall but of low chemical reactivity in the catchment (e.g. Na and Cl). The rainfall signal is damped, although there is some enrichment in the streams with decay over several weeks during wet-winter periods, when Atlantic inputs ensure a high-sea-salt loading (Neal *et al.*, 1988; Evans *et al.*, 2001; Neal and Kirchner, 2000; Feng *et al.*, 2004). A response to the atmospheric signal is also observed for Cr, especially during the 1980s (Neal *et al.*, 1996).
2. Under baseflow conditions the streams are of Ca and Mg,  $\text{HCO}_3$  type characteristic of waters that have reacted with the minerals in the bedrock. At high flows, streams are acidic and aluminium bearing and of low  $\text{HCO}_3$  content because of inputs from the acidic soils. The water quality thus varies with flow according to the relative proportions of the soil and groundwater inputs (Reynolds *et al.*, 1986; Neal *et al.*, 1990, 1997d; Robson and Neal, 1990; Hill and Neal, 1997). The variations in chemical concentration for baseflow and stormflow are provided in Table II.
3. There are annual cycles for nutrient components such as  $\text{NO}_3$ , Br and I because of the changes in decomposition rates in the soil and uptake by the vegetation (Neal *et al.*, 1997a).
4. There are longer term trends that are associated with the decline in acidic inputs (Neal *et al.*,



**Table II.** Arithmetic mean chemistry and arithmetic mean baseflow and stormflow chemistry for the period of felling in the lower part of the Hore catchment (1986–1987). Data for the Upper Hafren were not available at this time so the first two full years of data (1991–1992) from this site have been used instead

		Upper Hafren			Lower Hafren		
		Mean	Base	Storm	Mean	Base	Storm
Na	mg/l	3.47	3.55	3.22	3.69	3.70	3.59
K	mg/l	0.13	0.11	0.17	0.15	0.12	0.27
Ca	mg/l	0.53	0.64	0.38	0.86	0.99	0.69
Mg	mg/l	0.61	0.62	0.54	0.77	0.80	0.70
Cl	mg/l	6.14	6.13	5.69	6.40	6.12	6.74
SO <sub>4</sub>	mg/l	2.45	1.91	2.85	4.37	3.69	4.87
NO <sub>3</sub>	mg/l	1.13	0.82	1.23	1.40	0.99	1.58
DOC	mg/l	1.36	0.53	2.50	1.21	0.52	2.05
Si	mg/l	1.63	2.14	0.96	1.51	1.96	0.95
pH		5.62	6.44	4.72	5.28	6.32	4.50
Gran Alk	μEq/l	5	31	−21	−6	22	−34
ANC	μEq/l	−12	14	−32	−24	14	−62
Al	μg/l	96	25	211	233	45	444
Fe	μg/l	79	33	141	78	47	118
Mn	μg/l	19	15	17	36	22	44

		Upper Hore			Lower Hore		
		Average	Base	Storm	Average	Base	Storm
Na	mg/l	3.53	3.53	3.54	3.90	3.85	3.65
K	mg/l	0.12	0.10	0.13	0.24	0.18	0.37
C	mg/l	1.51	2.88	0.63	1.62	3.00	0.84
Mg	mg/l	0.70	0.85	0.60	0.91	1.12	0.71
Cl	mg/l	6.33	6.15	6.97	6.91	6.90	6.89
SO <sub>4</sub>	mg/l	3.86	3.21	4.19	5.12	4.93	4.83
NO <sub>3</sub>	mg/l	1.16	1.06	1.30	2.33	1.33	2.71
DOC	mg/l	1.34	1.04	2.21	1.21	0.78	1.98
Si	mg/l	1.28	1.77	0.88	1.42	1.89	1.02
pH		5.85	6.97	4.61	5.68	7.02	4.59
Gran ALK	μEq/l	30	125	−29	19	126	−26
ANC	μEq/l	12	113	−68	−8	95	−70
Al	μg/l	226	78	473	268	73	587
Fe	μg/l	82	78	103	73	78	105
Mn	μg/l	23	21	22	40	32	41

ANC, acid neutralization capacity; DOC, dissolved organic carbon.

2010). This is directly observed in the case of SO<sub>4</sub> and ANC and indirectly by an increase in dissolved organic carbon (DOC) (Monteith and Evans, 2000; Neal *et al.*, 2005) and Fe (Neal *et al.*, 2008) (Figure 3). In addition to annual cycles, NO<sub>3</sub> exhibits longer term (up to 5 years) variations that reflect the influence of large scale climatic drivers such as the North Atlantic Oscillation (Monteith *et al.*, 2000). The influence of forest harvesting is also seen especially at those sites where a large proportion of the catchment was felled over a short time span. We note that there has been a decline in both NO<sub>3</sub> and K in the last 5 years of record, which may link to the progressive re-establishment of the next generation of trees.

**Groundwater:** Groundwater was found in every exploratory borehole drilled across the catchments. Groundwater chemistry varied spatially from high-alkalinity waters, almost at levels observed in chalk aquifers, to acid waters characteristic of acidic soils. The groundwater represents fracture flow with transit routes for both deeper base-rich groundwater and shallower soil waters under wet conditions in the catchment (Haria and Shand, 2004; Shand *et al.*, 2005, 2007). Groundwater chemistry and flow are also highly variable over time. In one case, the introduction of a borehole within 20 m of the Tanllwyth stream channel completely changed baseflow chemistry for many years.



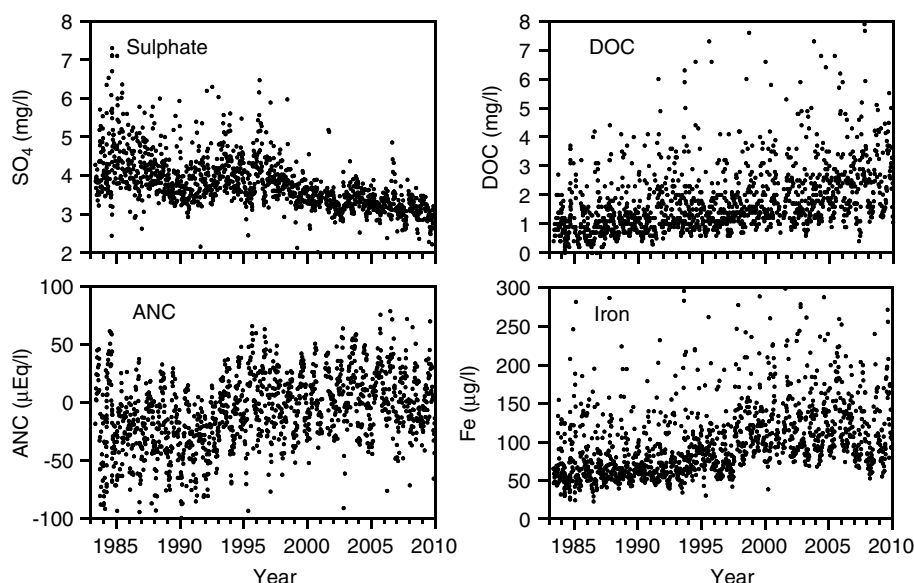


Figure 3. Time series of weekly concentrations of sulphate, ANC, DOC and iron in stream water at the Lower Hafren sampling site. ANC, acid neutralization capacity; DOC, dissolved organic carbon

*Forest harvesting impacts on water quality.* The major response to felling is primarily one of increased K and  $\text{NO}_3$  concentrations (Table II) that then decline after a few years following replanting and development of the next generation forest (Figure 4). In the case of the Upper and Lower Hore, there have been increased K and  $\text{NO}_3$  concentrations through 2007 and 2008 because of the recent felling of the upper part of the catchment (Figure 4). Thus, the Upper Hore monitoring point is no longer a control site for the Lower Hore. The decline in  $\text{NO}_3$  concentrations for the Lower Hore following the earlier phase of felling resulted in values lower than those observed before felling. Concentrations increased again at the time of the felling in the upper part of the Hore catchment as shown by the difference in concentration between the Lower Hore and the Lower Hafren (Figure 5).

Smaller increases in DOC and possibly Al and acidity (lower pH and lower Gran alkalinity) occurred soon after felling in the lower part of the Hore catchment, but the changes were insignificant compared with annual variability (Neal *et al.*, 1992a,b, 1998a,b; Neal and Reynolds, 1999a,b). Sea-salt concentrations also declined initially following felling as a result of reduced evaporation and scavenging of cloud water droplets and aerosols from the atmosphere by vegetation. However, the reductions were generally less than 1 mg/l and the concentrations increased again with the redevelopment of the forest up to the time of the felling upstream of the Upper Hore sampling point (Figure 5). Nonetheless, there were larger changes in the water quality response to felling at the local scale reflecting the highly heterogeneous system being examined (Neal *et al.*, 1998a,b; Neal and Reynolds, 1999a,b).

Two catchments exhibited much smaller chemical responses to felling that linked to the nature of the felling and the dominant soil type. In the case of the Hafren catchment, where felling was phased over many years, the water quality response is hardly noticeable (Neal *et al.*, 2004a). This is because any felling changes are diluted (a small proportion of the run-off changes in a given year), whereas in the case of  $\text{NO}_3$ , the enriched run-off from felled areas is partially counterbalanced by run-off from previously felled areas, where concentrations are depleted by the vigorous regrowth of ground vegetation and replanted trees. There were no clear changes in water quality associated with felling for the Tanllwyth catchment (on gley soils), and no clear  $\text{NO}_3$  pulse was seen at the catchment scale. Nonetheless, at the scale of the small ephemeral streams there were short-lived peaks in  $\text{NO}_3$  and  $\text{PO}_4$  resulting from the soil/biogeochemical disturbance. The reducing conditions prevalent in the gley soils will have increased mobility of phosphorus while limiting the formation of  $\text{NO}_3$  (Neal *et al.*, 2004b). For upland areas, the biological productivity of waters is limited with respect to  $\text{PO}_4$  with concentrations generally below 20  $\mu\text{g/l}$ . However,  $\text{PO}_4$  release with felling at the local scale probably resulted in increased biological activity in the main river channel that consumed any excess  $\text{NO}_3$  generated during felling (Neal *et al.*, 2004b).

The felling in the lower part of the Hore catchment represented an experimental clear cut completed in 2 years to maximize the response. It was never considered to represent 'real practice'. Indeed, the Plynlimon research when linked to earlier studies resulted in forest management guidelines recommending that felling is phased over several years (Neal and

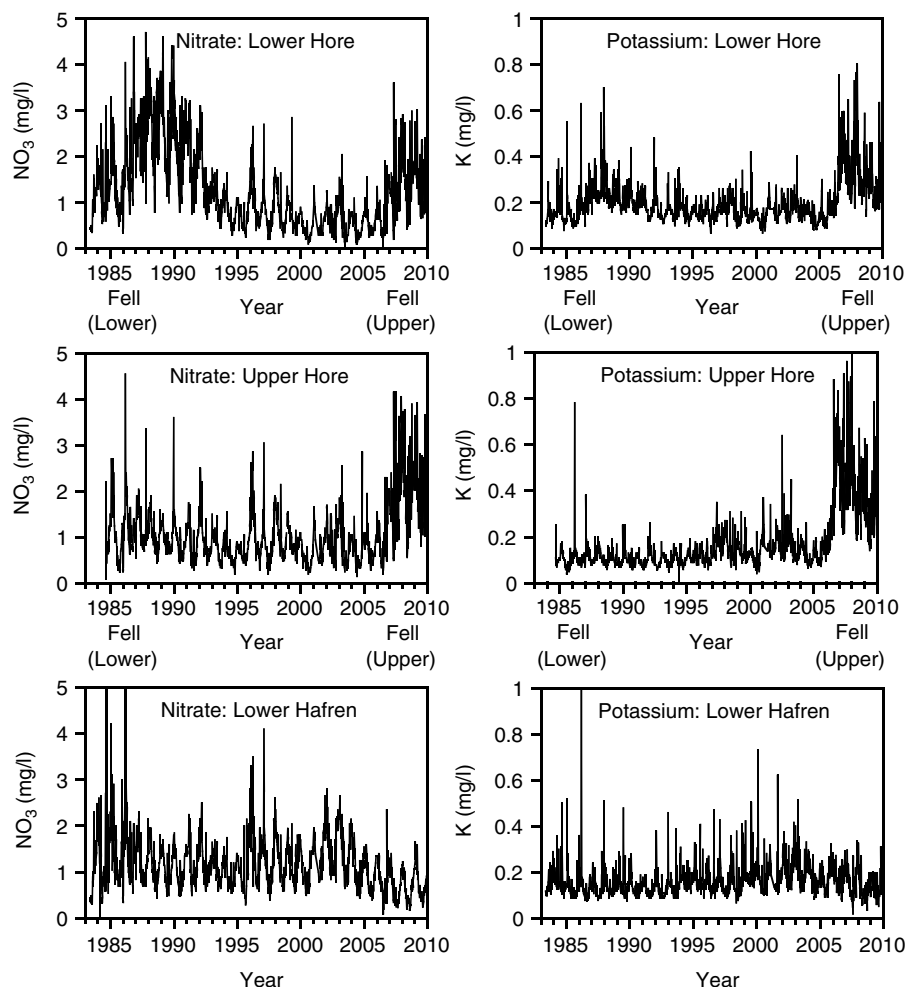


Figure 4. Time series of weekly concentrations of nitrate and potassium in stream water at the Lower Hafren, the Upper Hore and the Lower Hore sample sites

Reynolds, 1999a,b). The forest harvesting in the upper part of the Hore catchment was not experimental but indicates what can happen in practice. The changes were similar in magnitude to those observed for the earlier experiment in the lower part of the Hore catchment and had a marked impact on both the Upper and Lower Hore monitoring points. Suspended sediment levels have not been measured, but we note that at times during harvesting, suspended sediment concentrations were very high as the river was virtually opaque. This does not correspond to the requirements of good forestry practice.

## Conclusions, Lessons Learned and Recommendations

For almost 30 years, the Upper Severn has been monitored as part of a research programme examining the hydrogeochemical functioning and environmental management of upland river catchments. Numerous peer-reviewed publications have resulted linking to issues of catchment functioning, land use change,

atmospheric pollution and climate change/variability. The study shows that catchment functioning can be complex and that the water quality variations in the streams and in rainfall have changed over time in relation to hydrology and climate as well as in the case of the streams, because of forestry operations.

Now the stage is set to make the dataset fully available with minimum restrictions on access and use. This is in line with data policies of our parent bodies (CEH and NERC) and a much broader view that such data are of value to researchers and the broader community with an interest in the environment. Bringing the data together in an easily accessible and complete form has been challenging. The process of making data available in such complete form continues to develop, but further progress is required on a number of fronts. For example, there is a need for a detailed and consistent nomenclature for analytical determinands, a means for dealing with variable quality datasets and agreed conventions over the use of data, ownership and intellectual property rights. Indeed, there is the need for a step change that ensures

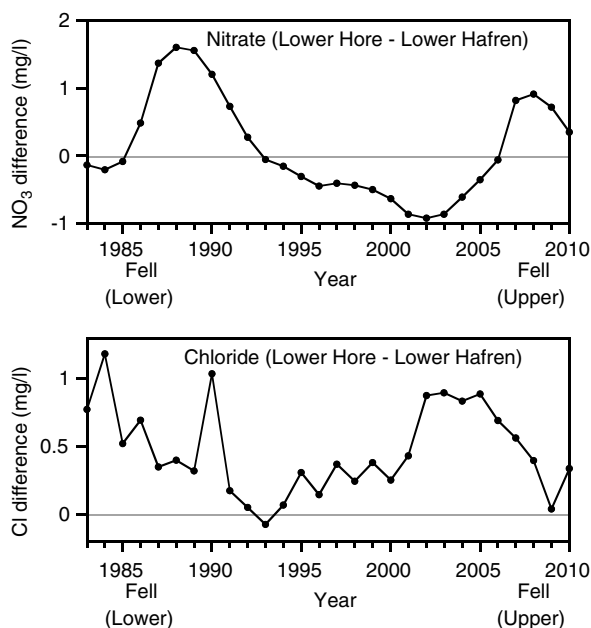


Figure 5. Time series plots of the differences in annual mean nitrate and chloride concentrations between the Lower Hore and the Lower Hafren sampling points.

from the outset that the data from publicly funded research will be made readily available. However, there are critical caveats: the researchers need time to fully publish their findings without pre-emption by others and the researchers' publications relating to the data must be cited in all publications arising from the use of the data by others. This article provides the key reference that should be cited when the water quality data from the Upper Severn are downloaded. Other publications will need to be referenced in relation to specific aspects of the study and findings. Further, as databases become linked, there is a need to ensure that these caveats are communicated and applied across databases and data centres. Such matters relate equally to the research community at large and to society. As such there is a need for agreed community protocols and funding.

In our case, the primary reasons to make our data available were threefold. First, we wished to organize our data to make them available at a time of staffing change where long-standing knowledge of the history of the programme, sampling and analysis is being lost. Second, we wished to use the data as a test case for the development of a web-based data portal within the context of the CEH Information Gateway with a spur to the development of a coordinated international framework of data collation, storage and dissemination. Third, we wished to make the data widely available especially for education and research purposes. On the research front, there are changing water quality trends and behaviours that require explanation and different approaches and

skills to ours. Such skills include time series and spectral analysis, dynamic and long-term modelling and comparative studies and thermodynamic analysis. We have deliberately provided uncensored data as this maximizes the opportunity to interrogate the data, although the analytical protocols and detection limits allow informed constraints to be applied. For the broader community, there is a need for an interface that allows some censorship as non-specialists may not understand the meaning of analytical uncertainty. In this sense, our and other CEH datasets on the CEH Information Gateway provide a resource for exploring a community-wide approach to data sharing.

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