PLYNLIMON HYDROMETRIC REVIEW 2009

WITH SPECIAL REFERENCE TO THE DECADE 2000-2009

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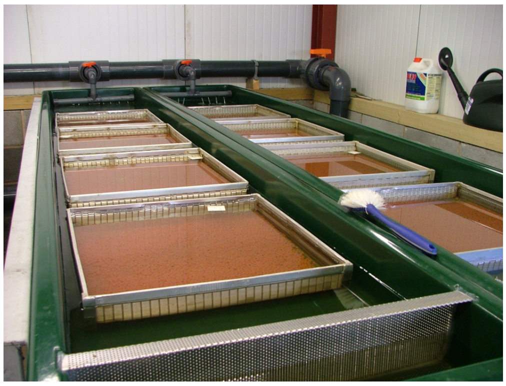


1. River Severn source among eroding peat haggs; UK peatlands are a major carbon store.
2. Pipeflow emerges after rain; indicative of multiple flow processes operating.
3. Enormous range of flows; the UK uplands contribute to major floods downstream
4. Fishing is an important economic resource in the region; Clywedog hatchery can produce up to 350,000 Atlantic salmon a year for introduction into the River Severn.

CEH 2010

CONTENTS

Earlier CEH Reports in this Series

Grant, S.J. and Robinson M. (2007). *Plynlimon Hydrometric Review 2005-06*

Grant, S.J. and Robinson M. (2008). *Plynlimon Hydrometric Review 2007*

Grant, S.J. and Robinson M. (2009). *Plynlimon Hydrometric Review 2008*

INTRODUCTION

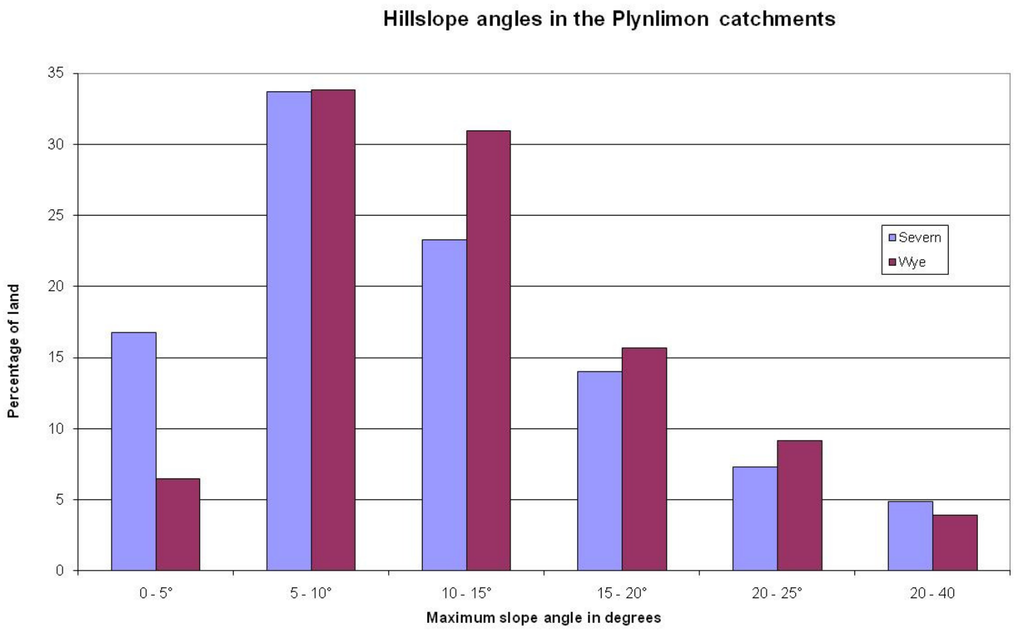
It is now a decade since the transfer of Plynlimon data processing was fully implemented at Wallingford, following the closure of the Dolydd catchment office. The **core hydrometric network** comprises 8 streamflow gauges, providing 15-minute discharges, and 4 automatic weather stations (AWS) recording hourly data. These data are held on a secure **Oracle database** containing measurements back to 1968. Recent hydrological publications have included the impacts of felling on stream regimes (Robinson and Dupeyrat, 2005) and changes in the long-term water balance (Marc and Robinson, 2007) which revealed for the first time the non-stationarity in water use of a relatively even-aged UK plantation forest.

As well as dealing with processing and quality controlling the streams of flow and weather data the transfer of responsibilities to Wallingford included cataloguing a large amount of paper records, maps and documents. Where possible legacy metadata concerning the flow and weather data are captured from notebooks and diaries and have been put into electronic form. Beginning in 2000 more systematic detailed **electronic metadata records** have been maintained, and this information is held on a secure network drive accessible by Bangor and Wallingford staff. This metadata includes records of specific instrument changes as well as broad data issues such as extended periods of several weeks of missing data (as notably occurred due to access restrictions during the 2001 outbreak of Foot and Mouth Disease).

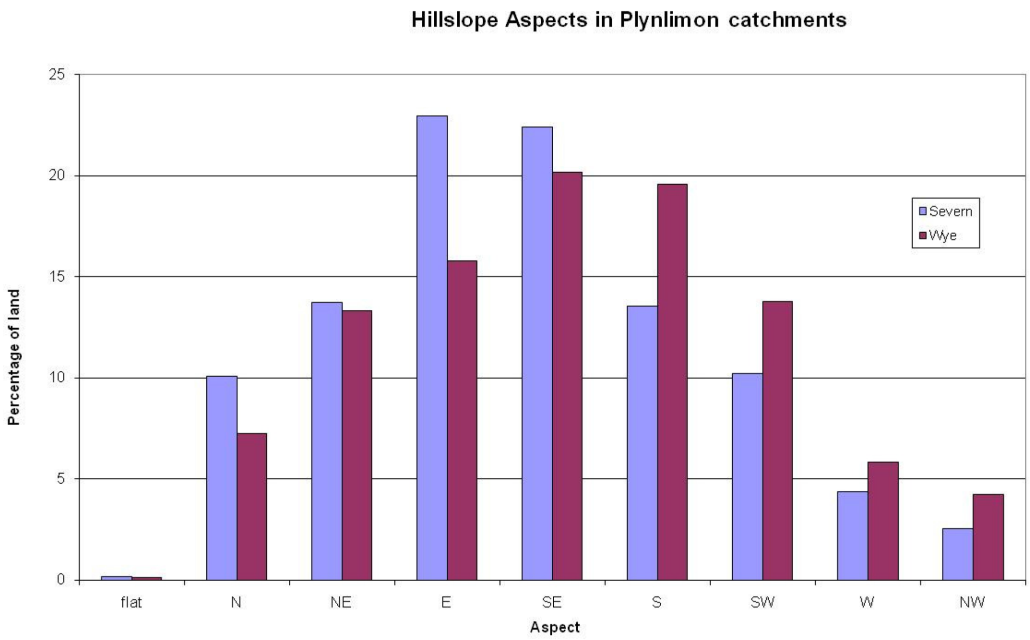
With the centralisation of work at Wallingford the opportunity was also taken to digitise many of the catchment information maps. These include the original 1:5000 maps commissioned from *Huntings Surveys* of the topography and stream networks, as well as specific surveys including vegetation, soils and forest extent. The field instrument locations were determined using GPS. A summary and description of this **spatial data archive** has been published (Brandt et al, 2004), and some of the spatial data sets free of third part licence restraints are now available for download via the **CEH Information Gateway** (http://gateway.ceh.ac.uk/).

Figure 1. Comparison of the topography of the two catchments

a) Slope



b) Slope direction (aspect).



BACKGROUND

The Plynlimon paired catchment study was established in direct response to the needs of government policymakers concerned about future water shortages, and the potential role of land cover (Robinson, Rodda and Sutcliffe, *submitted*). In essence it compares forest and moorland/improved grassland.

The study was established to consider and quantify the likely impacts of afforestation in the form of commercial conifer plantations. As a consequence of the studies at Plynlimon and subsequent research in the UK uplands there is general agreement that the replacement of short vegetation covers, such as grassland or moorland, by mature coniferous plantation forest will tend to increase the proportion of rainfall lost to the atmosphere via evaporation. This is principally due to high rates of interception loss from the tree canopy, rather than significant differences in transpiration rates. Plot studies measuring interception losses supported the catchment scale findings. Calder and Newson (1979) summarised the results of these studies; suggesting that forest interception losses are equivalent to 30-35% of annual precipitation in areas receiving more than 1000mm. Soil water measurements generally indicate drier conditions under forests than grasses (Hudson, 1988), reflecting the higher interception rates that lead to lower net rainfall to the soil. The findings from many studies on upland losses have been drawn together in the form of a semi-empirical model known as the Hydrology of Land-Use Change (HYLUC) model (Calder, 1990).

The study site in the uplands of Wales has mountainous topography with altitudes ranging from 320 to 740m, and slopes typically of 5 to 15 degrees. The soils on the steep mountainous slopes tend to be shallow and to shed water readily. Numerous channels run down from the steep slopes to the main watercourses in the valley bottoms. The geology is very uniform comprising mostly layer on layer of shales and mudstones, with little to differentiate them. The rocks were formed at the bottom of the ocean in the Palaeozoic and are basically mudstones with varying degrees of metamorphosis mainly during the Caledonian orogeny. The surface layers were formed by glacial deposits –

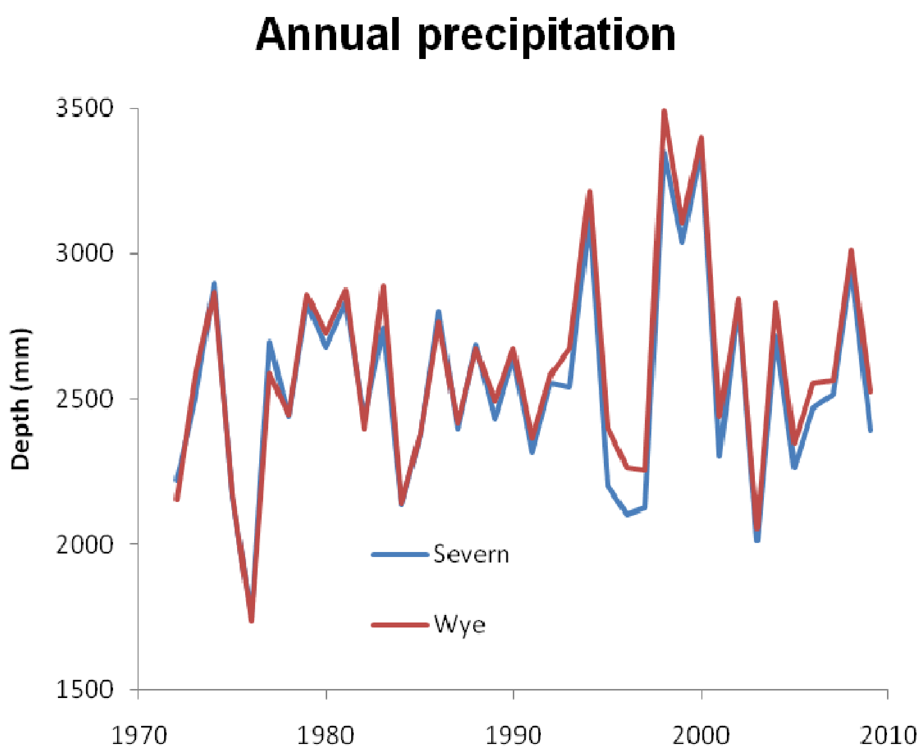
rock flour (boulder clay) of a couple of metres thick with thicker deposits in the valleys. Given that the geology is very uniform the main soil groups at Plynlimon are determined by the topography, so there is a relatively simple situation to study the relation between soils and slopes (Bell, 2005).

This Review describes the streamflow and weather data collected in the Plynlimon catchments with particular attention to the decade 2000-9.

CLIMATE

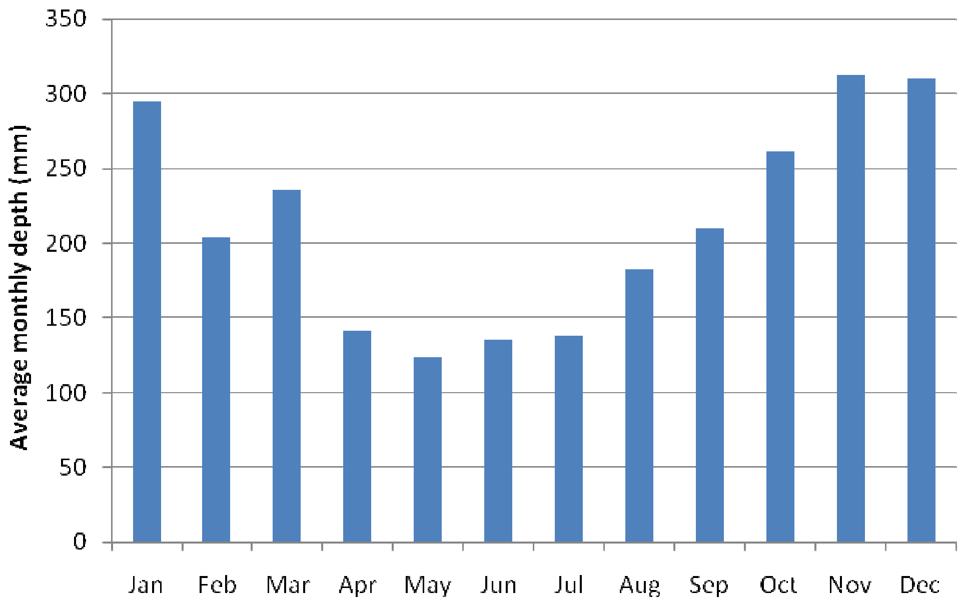
The long-term average annual precipitation for the catchments is about 2600mm. The 2000s were preceded by a series of exceptionally wet years, even for Plynlimon. The 3 years 1998-2000 were the 3 wettest since records began in 1972 and 2008 was the fifth wettest year. The annual rainfall of over 3000mm was substantially above the long-term average.

Figure 2. Long-term storage gauge network catchment areal average depths



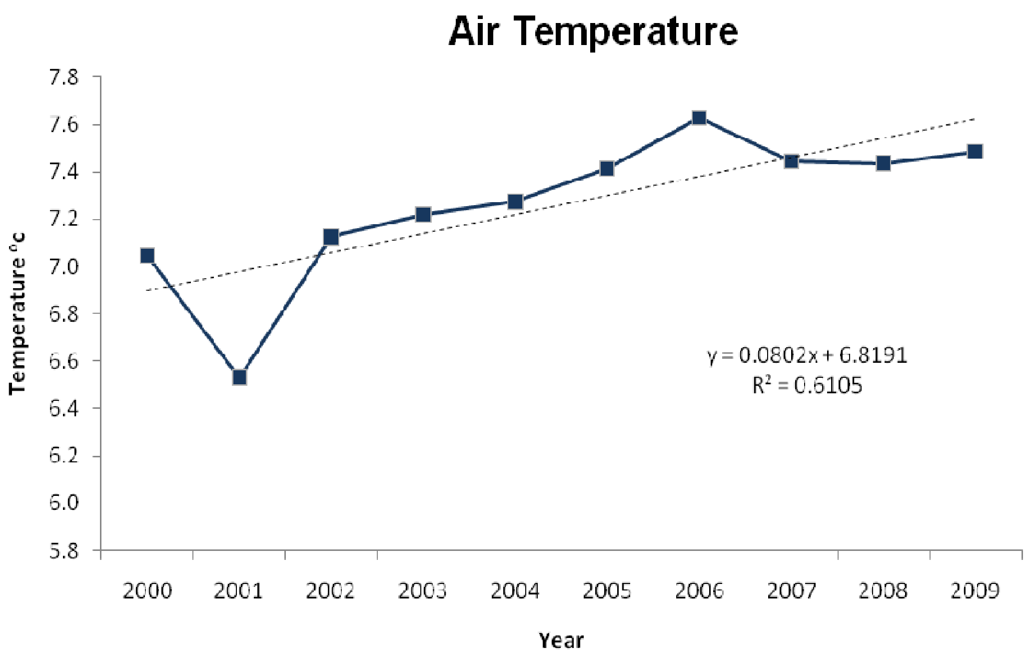
From a seasonal perspective October to January are the wettest months, with April to July being the driest months of the year. Potential evaporation (Penman short grass) for the catchment is about 500mm per year.

Figure 3. Average monthly precipitation



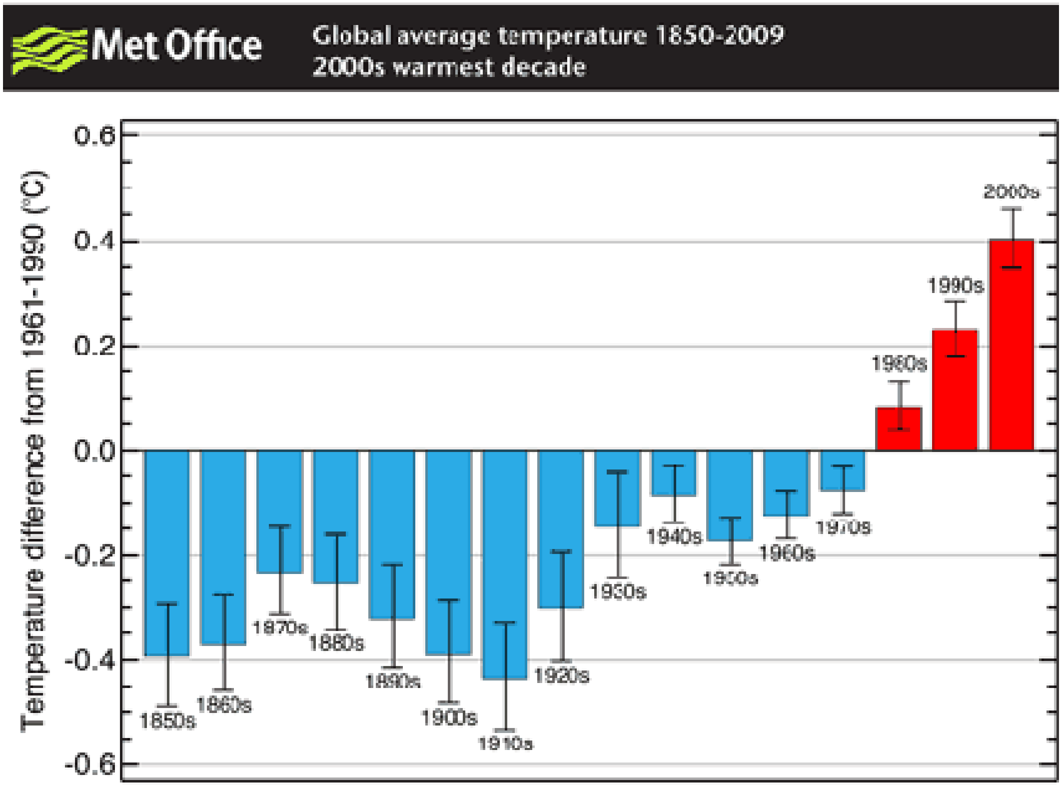
The average air temperature has increased slightly over the decade .

Figure 4. Mean annual air temperature 2000-9



The first decade of this century has been, by far, the warmest decade in the 160-year record of global surface temperature, maintained jointly by the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia.

Figure 5. Global temperature variations



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Despite this apparent warming trend, and the decade 2000-9 beginning with relatively mild conditions, the winter of 2008-09 was severe, being the worst for almost 20 years and the following winter (just outside this review period) was the coldest in the UK for 30 years.

WEATHER VARIABLES

The long-term average values of the main weather variables are listed below for the three principal AWS: Carreg Wen (575 m AOD) is at the top of the Severn, Eisteddfa Gurig (530 m) is near the top of the Wye and lower altitude Gwy AWS (380 m) is near the middle of the Wye catchment and experiences much lower wind speeds.

Table 1: Average AWS values for the decade 2000-9.

Variables and Units	Carreg Wen	Eisteddfa Gurig	Gwy
Solar Radiation (W/m^2)	105.74	96.31	101.78
Net Radiation (W/m^2)	51.73	48.16	47.37
Air Temperature (°C)	7.31	7.77	7.88
Wind speed (m/s)	4.35	4.41	2.96

In the last Review (2008) a study of long-term solar radiation records found no detectable signs of changes in the recorded values over the last 30 years.

Table 2: Average values for different time periods at different AWS. Values for the 2000s decade examined here are shown in blue.

	Altitude (m)	Period	Air T (°C)	Solar (W/m^2)	Net (W/m^2)	Wind (m/s)
Eisteddfa Gurig	530	1975-09	6.94	93.12	46.44	4.63
		2000s	7.77	96.31	48.16	4.41
Gwy	385	2000s	7.88	101.78	47.37	2.96
Nant Iago	400	1978-83	7.30	94.78	38.99	3.22
Cefn Brwyn	355	1975-99	7.88	96.77	49.83	3.29
Carreg Wen 1	575	1975-99	6.13	96.90	50.19	4.15
Carreg Wen 1*		2000-05	6.67	93.56	50.89	3.25
Carreg Wen 2	580	2000s	7.31	105.74	51.73	4.35
Tanllwyth*	350	1975-99	7.09	94.19	47.93	1.27
Tan (mid)		2003-9	8.32	103.76	55.25	2.26

**Over-sheltered site*

Eisteddfa Gurig has the longest uninterrupted series and shows broad similarity between the whole 35 year period of record averages and the 2000s; with evidence of a small increase in air temperature and possibly radiation (Table 2). It can be used as a 'control' site for the other AWS in the Severn catchment, for which there is evidence of progressive over-sheltering due to forest growth. The **Carreg Wen** site was known to be overshadowed and a new AWS site was installed in 2001 and run in parallel. At the original site (CW1) the wind speed had been declining (from 94% to 84% of the Eisteddfa Gurig value) and was ~25% lower than at the new, better exposed site (CW2): i.e. 3.25 vs. 4.35 m/s.

Similarly, the **Tanllwyth** AWS had also been getting sheltered by forest growth: with a mean wind speed of 1.14 m/s (1992-99), cp 2.26 for new site (2003-9).

Table 3: Reduction of wind speed at Carreg Wen and Tanllwyth.

	Period	Air T (°C)	Solar (W/m^2)	Net (W/m^2)	Wind (m/s)	Wind/ E. Gurig
Eisteddfa Gurig	1975-82	6.43	95.18	47.61	4.74	-
	1983-91	6.37	94.52	43.57	4.96	-
	1992-99	6.86	97.12*	46.72	4.53	-
Carreg Wen 1	1975-82	5.71	93.50**	50.26	4.46	0.94
	1983-91	5.77	99.75	52.44	4.26	0.86
	1992-99	6.77	96.80	48.11	3.82	0.84
Tanllwyth	1975-82	6.80	95.18	46.96	1.44	0.30
	1983-91	7.32	94.63	46.48	1.27	0.26
	1992-99	7.07	92.56	42.69	1.14	0.25

**Excl 1999 suspect data, otherwise 87.24* ***Gaps in summers reduced average*

Further work on quality control and analysis of the historic climate data collected at Plynlimon is in hand.

There is a clear relationship between average wind speed and site altitude. Excluding the most sheltered periods there was a strong linear relationship indicating mean wind speeds typically increase from about 2.8 m/s at 350m altitude to 4.4 m/s at 550m:

$$\textit{Mean wind speed (m/s)} = 0.008 \textit{ Altitude (m)} \qquad (r^2=83\%)$$

There was a weaker reduction in air temperature with increasing altitude:

$$\textit{Mean air temperature } (^oC) = -0.004 \textit{ Altitude (m)} + 9.34 \qquad (r^2=60\%)$$

This indicates air temperature decreases on average by about 0.4 ^oC / 100m increase in altitude. The dry adiabatic lapse rate is about 9.8 ^oC / 1000m, with lower rates of decrease with altitude expected for humid air. The International Civil Aviation Organization, for example, defines an international standard atmosphere as having a temperature lapse rate of 6.49 °C/1000 m. With a higher than average air humidity the Plynlimon value of 0.4 ^oC / 100m is reasonable.

As expected there was no relation between solar radiation and altitude. The main local influence is site exposure; hence the lower values for the over-sheltered Carreg Wen 1 and Tanllwyth AWS (especially shaded at low sun angles). Solar and net radiation values averaged across the 3 best exposed AWS (Eisteddfa Gurig, Gwy and Carreg Wen 2) are shown below for the period 2000-9.

Figure 6. Daily mean solar radiation (W m^{-2}) over the decade 2000-9

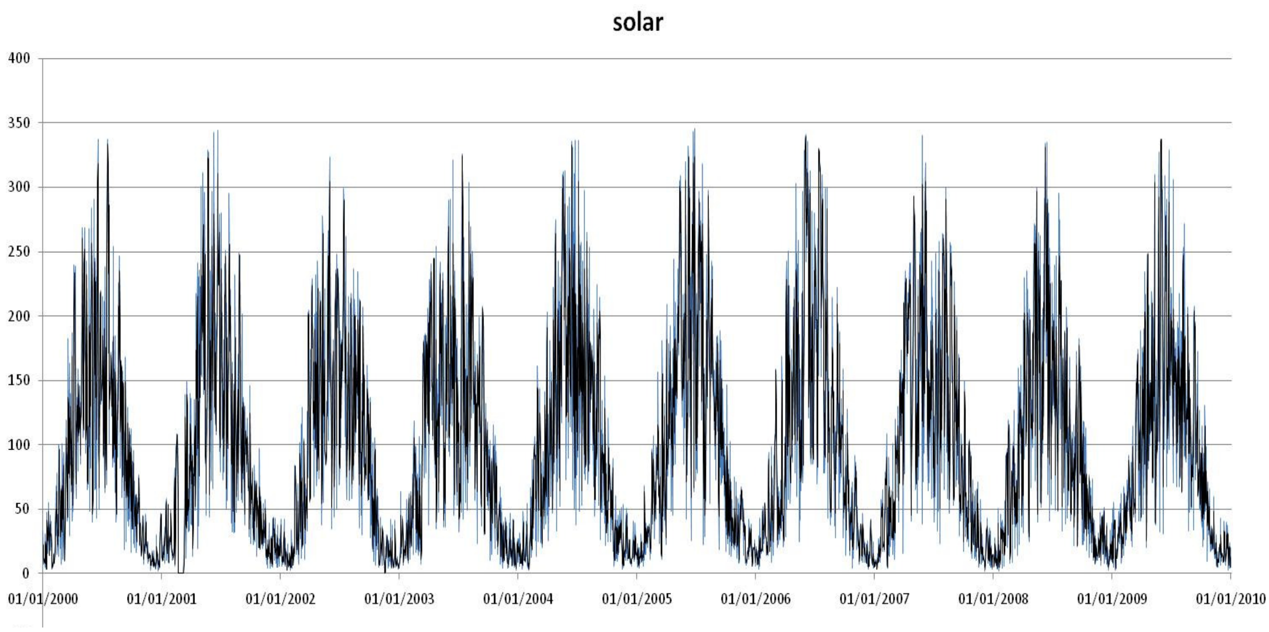
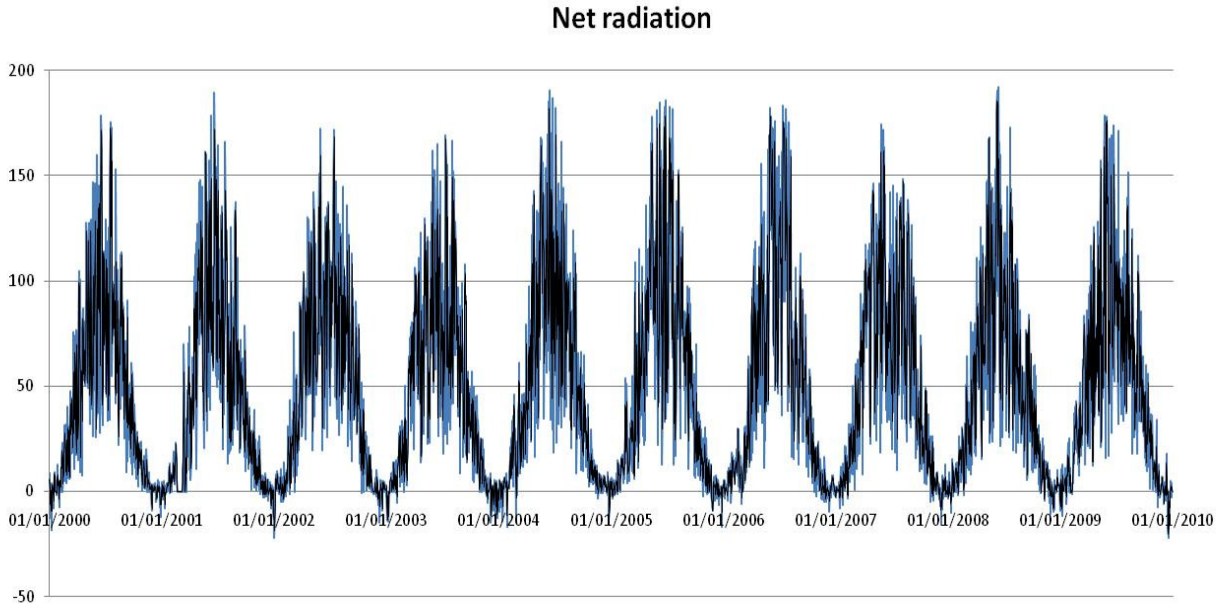


Figure 7. Daily mean net radiation (W m^{-2}) over the decade 2000-9



STREAMFLOW

Extensive flow data exist for the main catchments of the Severn (8.7 km^2) and the Wye (10.55 km^2) and their sub-catchments:

a) Grassland Wye and its two gauged subcatchments: Cyff and Gwy

b) Forested Severn and gauged subcatchments: Hore, Tanllwyth and Hafren.

The detailed 15-minute data are available via the CEH Gateway and daily mean flow measurements are passed on to the National River Flow Archive which holds and makes available flows for all of the catchments. Additional background information is available at: http://gateway.ceh.ac.uk/

As a check on their magnitudes, flow regimes and timing, the measured flows are first plotted as time series with the rainfall inputs.

Figure 8. Daily mean flows (m^3 s^{-1}) 2009

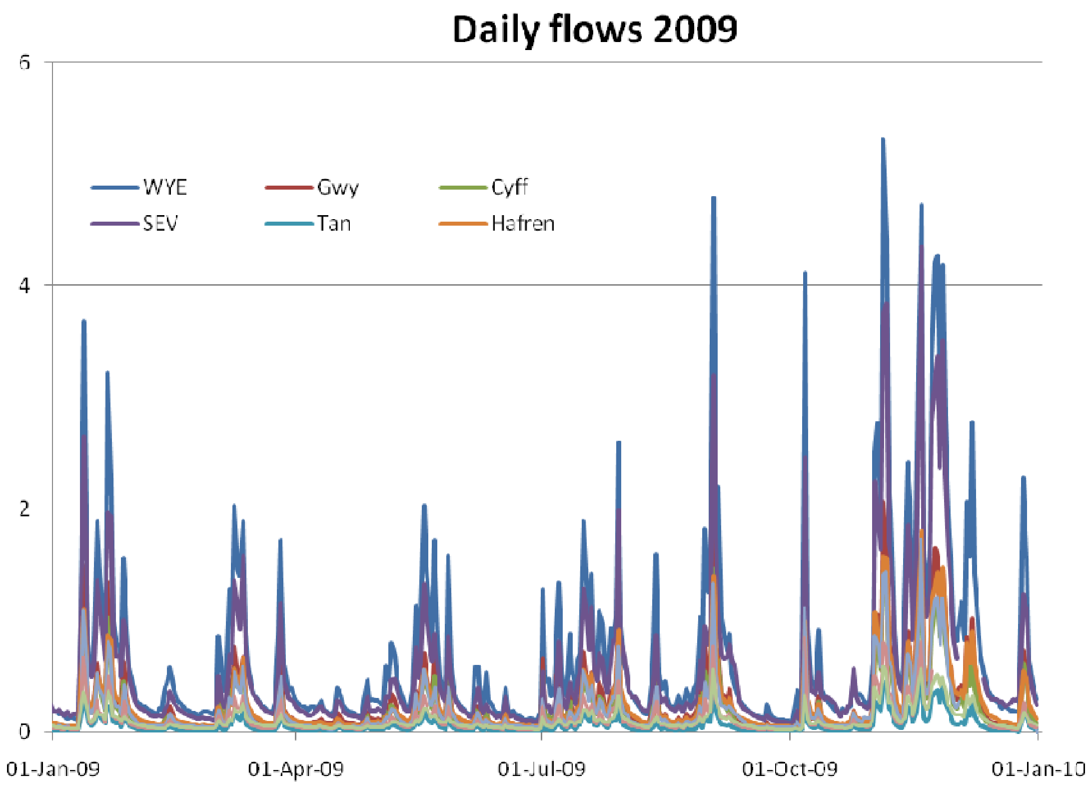
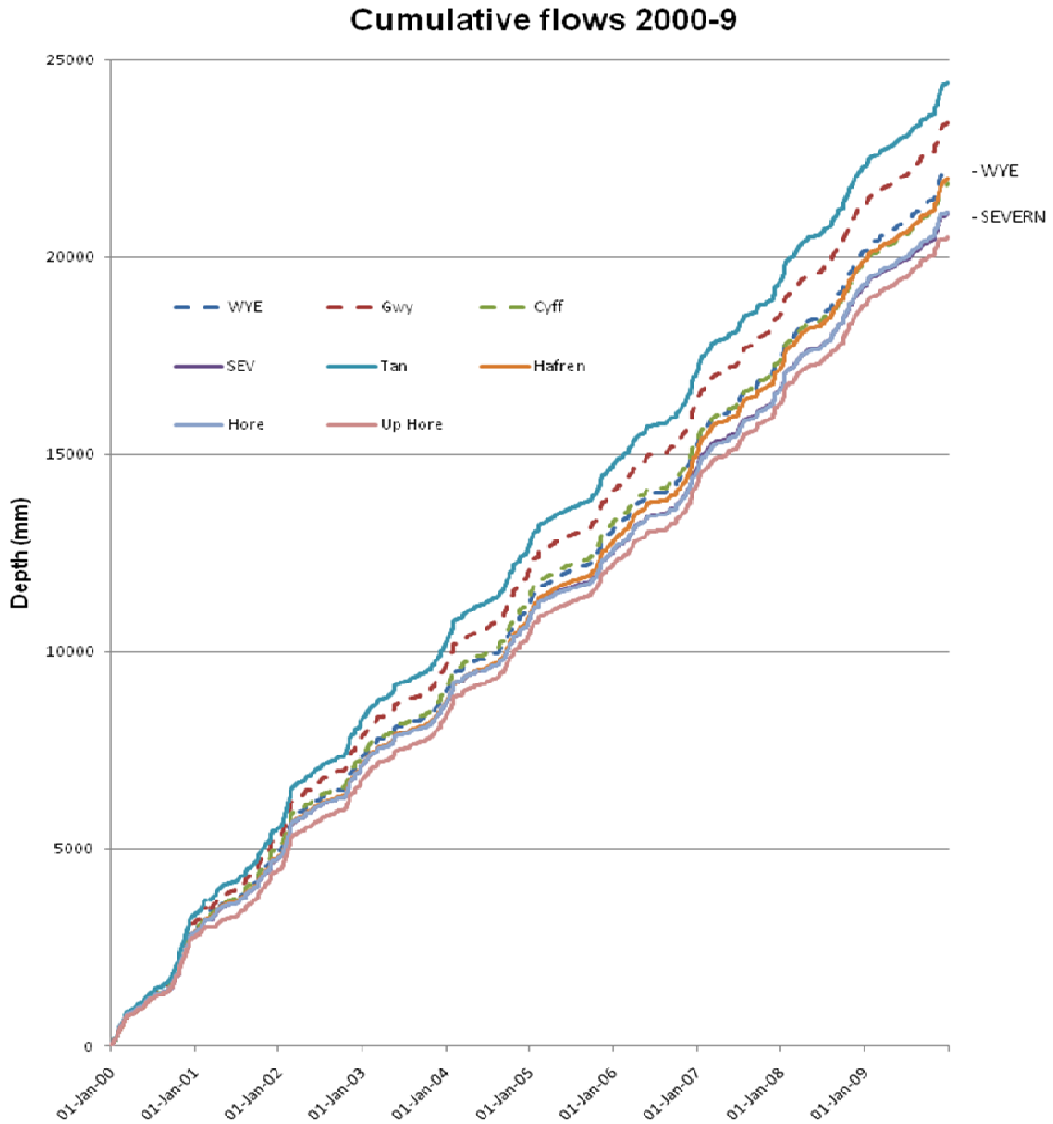


Figure 8 shows time series of daily gauged flows (m^3/s) for: a) Severn, b) Wye catchments for 2009. There was very close agreement between the flow series, responding in unison to storms events. As a useful form of additional checking, they were inter-compared as cumulative plots of runoff *depths* (mm) to remove the effect of differences in catchment area. The forested basins are shown by continuous lines and the grassland basins with dashed lines.

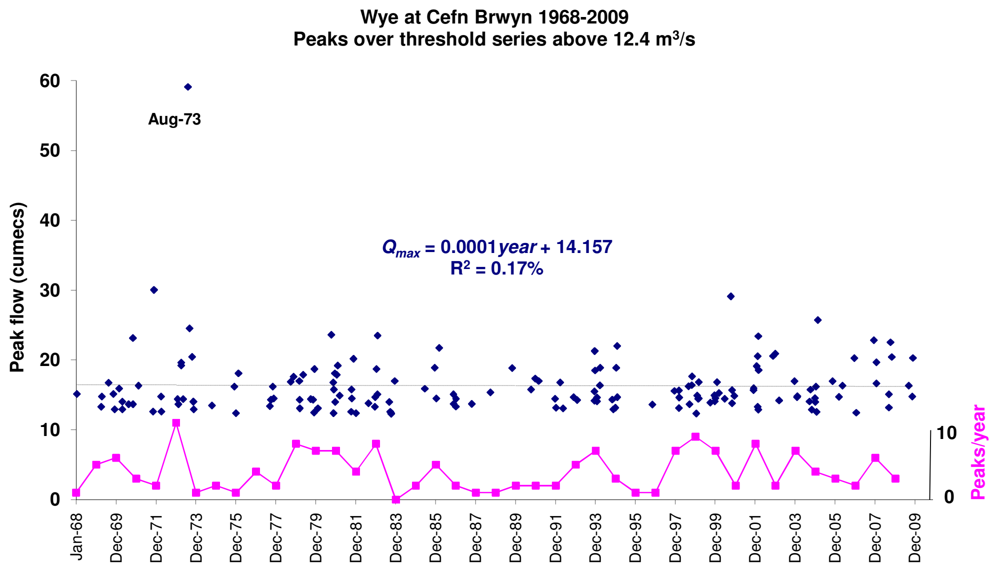
Figure 9. Cumulative flows (mm) 2000-9

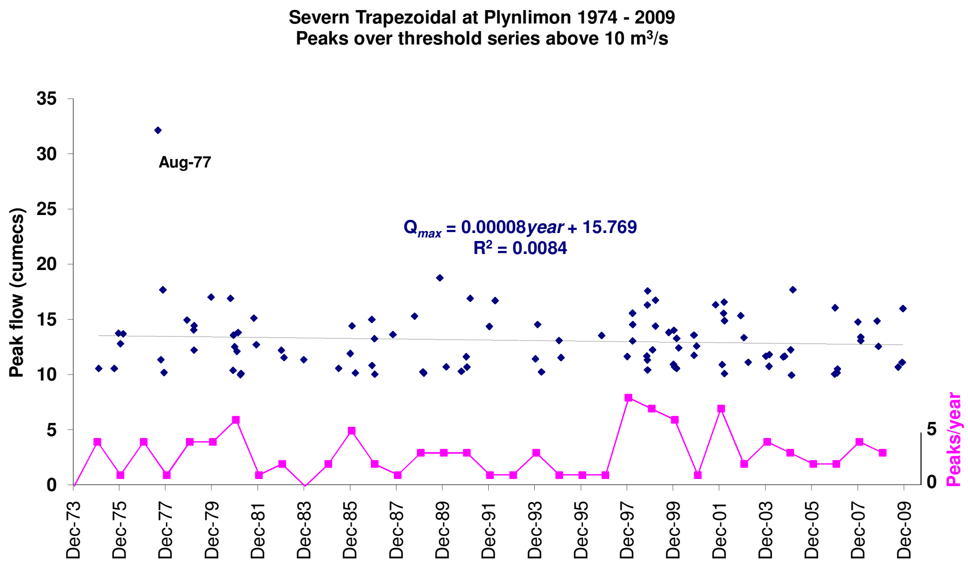


As expected the main Wye catchment (grassland) and its sub-catchments have higher flows than the Severn (mostly forest), and its sub-catchments. The exception is the Tanllwyth gauge which recorded a greater depth of flow than the other subcatchments. The possible cause, including the drilling of a borehole nearby, is still under investigation.

There is no evidence of a change in peak flows of the two main catchments. The flood series of the forested subcatchments that underwent concentrated felling is being investigated (Robinson et al. in prep.).

Figure 10. Peak flows and number of occurrences





CATCHMENT WATER BALANCES

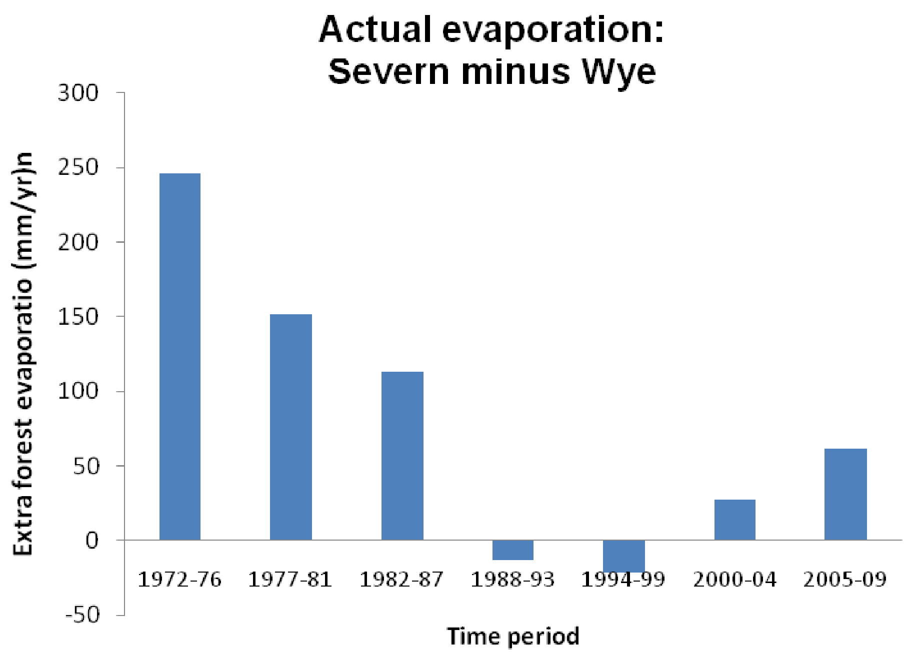
The annual rainfall and runoff for the main catchments (mm) are given below for 2009, the year under review, together with whole decade (2000-9) and the long-term average since 1975 when all gauges were operational. The precipitation is based on the areal network of approximately 30 monthly-read storage gauges.

Table 4: Main components of the catchment water balances.

	Streamflow		**Precipitation**		**Evaporation**	
	Severn	**Wye**	**Severn**	**Wye**	**Severn**	**Wye**
1975-1999	1968	2079	2536	2583	568	504
2000-2009	2118	2238	2582	2657	463	419
2009	1885	2100	2394	2524	509	424

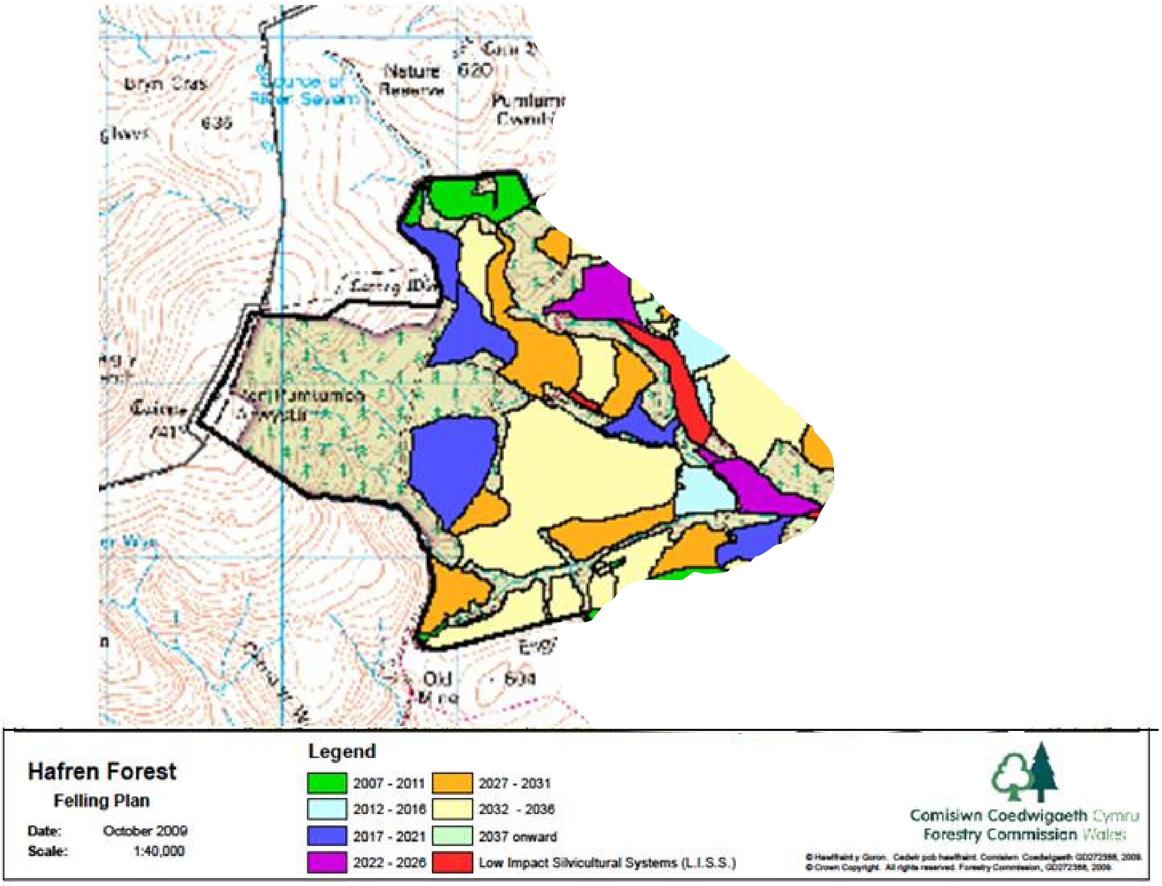
Looking firstly at streamflow, the lower flows from the forested Severn catchment are clearly apparent. Figure 11 extends the pattern of changing forest water use relative to grassland presented in Marc and Robinson (2007).

Figure 11 Difference in evaporation (P – Q) between the catchments



With the continuing felling, the extent of the planted area comprising first rotation forest declined from about 50% of the total forest in 2000 to under 20% by 2010. Much of the original plantation that remained was thinned to create Low Impact Silvicultural Systems (LISS).

Figure 12. Felling plan for the Hafren. Areas due to be felled in the next decade (first column) are first rotation forest.



DISCUSSION AND CONCLUSIONS

This decade report has confirmed that streamflow and weather data were of good quality and mostly without breaks. The continuing requests for catchment data from the UK and international research community (see below) show that the data remain relevant to current issues.

The Plynlimon catchments continue to be relevant to many current issues:

Long-term trends of climate. Weather variables show much year-to-year variability but there is no evidence of a long-term trend with the possible exception of air temperature.

Catchment land management impacts on flow regimes. The felling effects on streamflow remain a topic of great concern. Despite the substantial amount of felling and regrowth at Plynlimon, there is no evidence of detectable changes in flood peaks indicating that properly managed silviculture can result in forestry having only a limited negative impact on flood risk. The findings at Plynlimon are being incorporated in a joint multi-catchment and multi-organisation science journal paper (Robinson et al., in prep).

Future plans:
Beginning in 2005 we progressively developed and rigorously tested procedures for data presentation, testing, and fault identification. Following favourable responses from data users we began to apply these techniques to the historic data archive, and as far as possible began to include the assimilation of their associated contemporary metadata in digital form. This task will make it much easier for researchers to use and interpret the data. This will now continue back in time from 2000 to deal with the 30+ years of data prior to the transfer of data collection and processing responsibilities from the Plynlimon catchment office. As with the previous Reviews this information will be made available electronically on the CEH Website. With the release of the chemistry dataset it is hoped to incorporate some of those data in forthcoming retrospective Reviews alongside the hydrology.

Hydrological records supplied to support CEH and University research and partner organisations during the decade included:

UK Universities:

Aberystwyth – Jones, Macklin, Briers,
Birmingham - Hannah, Lawler, Jones
Cardiff – Ormerod, Hales, Lewis,
Imperial - Wheater, Onof, McIntyre
KCL – Cloke, Bark,
Lancaster – Freer, Romanowicz, Page,
Leeds – Holden, Clark,
Loughborough – Reid,
Newcastle – Bathurst, Calder,
Nottingham – Mount, Parker,
Sheffield – Evans, Pellenq,
UCL – Snell,
UEA – Ness.

Overseas Universities:

Berkley, Penn State (US), Melbourne (Australia), Aas (Norway)

UK organisations:

Cascade Consulting (for EA project), Environment Agency, Jeremy Benn Associates (for EA project), Wallingford Hydro Solutions.

CEH Project staff requests:

Billett, Bonjean, Cooper, Cullen, Evans, Frogbrook, Gordon, Haria, Hughes, Hutchins, Laize, Neal, Norris, Oakley, Reynolds, Sowerby.

Projects supported by the use of Plynlimon data include:

Acid Waters Monitoring Network, Fractal process studies, National River Flow Archive, ECOSSE carbon and nitrogen modelling, ForestClim.

In future, easy access to data straight from the CEH Information Gateway means that direct contact with data users will inevitably be eroded, giving greater importance to these regular data Reviews.

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APPENDIX

Quality control checks

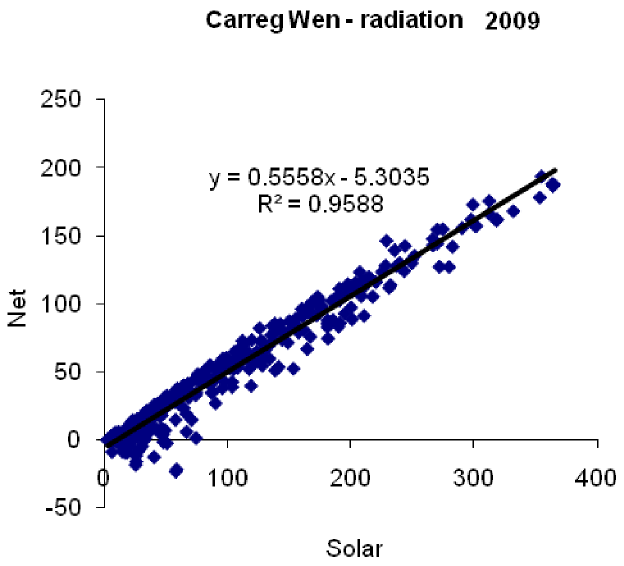
Automatic weather stations are serviced at 6-month intervals in the field. The temperature sensors (wet and dry) and the solar radiometer are re-calibrated (Grant, 2009). Checks are made on the operation of the anemometer, wind vane and the tipping bucket raingauge. Back in the office we check the data in four independent ways: average values and ranges, time series plots of amounts and timings, 'internal' (i.e. inter-sensor at a site), and 'transposable' (between site) comparisons. Any apparent anomalies can be reconciled against metadata records.

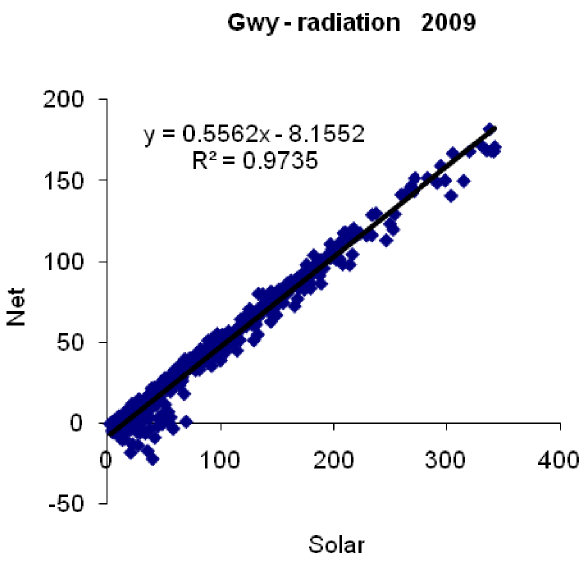
Figure 13 shows the relationship between the Solar and Net radiometers at each site. As a *rule of thumb*, over grass Net radiation = $^{2}/_{3}$ Solar (except when snow is lying on the ground). There was close relationship (R^2 >94%) at each AWS, with a regression slope of ~0.5-0.6.

The next suite of checks is between the 'transposable' (i.e. non-site specific) meteorological variables at pairs of sites. These include solar radiation, air temperature and perhaps rainfall, but not local wind. Figure 14 shows a very consistent relationship (R^2 >95%) between sites for solar radiation.

Overall, these checks confirm the high quality and consistency of the AWS data.

Figure 13. Solar and Net radiation (W/m^2) at each AWS.





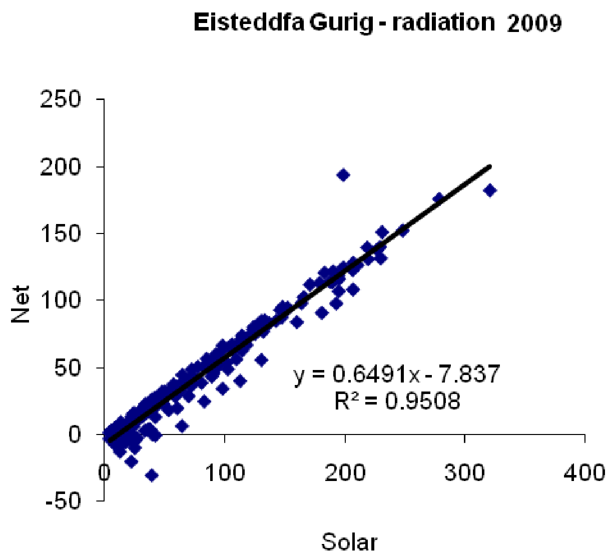
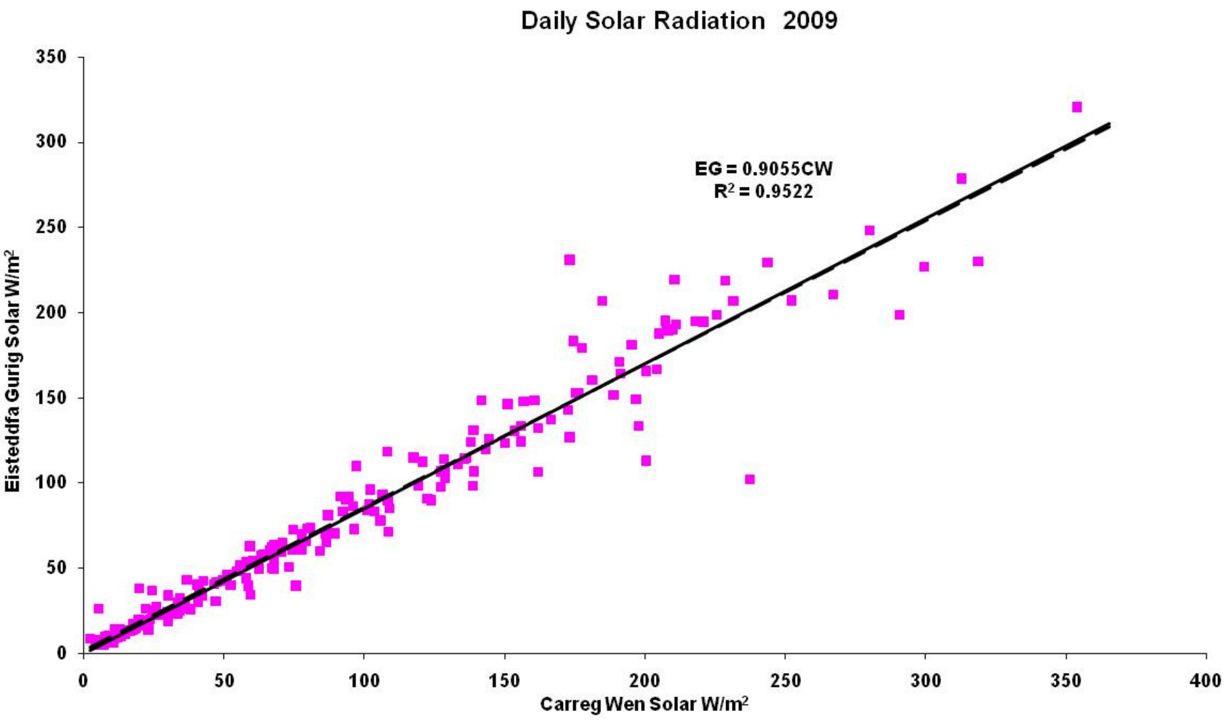


Figure 14. Solar radiation (W m^{-2}) comparison between AWS sites



Storage raingauge network overview.

The Plynlimon raingauge network collects essential data for the Plynlimon catchment water balance calculations. It currently comprises 26 large capacity *Octapent* storage gauges which are emptied at approximately monthly intervals. Ground level, standard and canopy gauge types are deployed. The gauges are dispersed over the catchments in domains defined by combinations of classes of altitude, slope and aspect.

The gauge network requires constant preventative maintenance to maintain valid data collection. Work includes clearing growing vegetation (grass, shrubs and trees), blockages due to leaf and needle litter, replacement of rotting gauge pit wood, water ingress into gauge outer chamber, damage due to tampering, livestock or farm machinery. Emptying all 26 gauges over one day is normally achievable, but problems can arise in poor weather conditions (deep snow or very heavy rain) especially in winter, when daylight is limited, then access to the high altitude gauges can be difficult.

The majority of the gauges work well but in the decade 2000-2009 four gauges did perform as well as hoped – Cyff A1Y, Hore A3Z, Severn A2Y, Wye B2W. The reasons and solutions are recorded below.

Cyff A1Y

Ground level gauge Cyff A1Y was located next to a subsurface stream which began to overspill and flood the rain gauge pit during heavy rain then more frequently thereafter. After several years of flooding, the gauge was relocated 30m to the north on slightly raised ground in May 2009. A mechanical excavator was required to dig the rain gauge pit due to the heavy shale in the area.

Hore A3Z

Canopy gauge Hore A3Z suffered sheltering from growing trees from September 2004 to February 2006. The gauge was located on a steep, exposed, forested slope and even though the immediate area around the gauge was open, sheltering was occurring. A wider area should have been cleared at an earlier date to prevent this. The area was felled in early 2006 alleviating the problem.

Severn A2Y

Canopy gauge Severn A2Y (mature trees 18m) was damaged during a storm (winter 2008) when a tree limb bent the collection funnel. It was thought that a blockage was caused by pine needles or bird droppings (canopy gauges can be used as occasional perches by large birds - Buzzards and Kites) but when the blockage could not be removed the mast was climbed to reveal funnel damage. Two close proximity mature conifers were felled and several attempts were made to replace the funnel which had seized fixings – it was also noticed that the masts supporting guy wires were in poor condition and funnel replacement was abandoned awaiting mast repair.

Wye B2W

Ground level gauge Wye B2W was crushed during mowing operations by a tractor in April 2010. This gauge was repaired in November 2010.