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45 years of non-stationary hydrology over a forest plantation growth cycle, Coalburn catchment, northern England

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Abstract

The Coalburn research catchment (1.5 km²) in Kielder Forest, Northern England, is a long-term project to study the effect of upland afforestation on hydrology. There is now a unique 45-year record; making it Britain's longest running forest hydrology research catchment. The site was instrumented in 1967, ploughed and planted in 1972/73 and the trees have now reached maturity. Hourly meteorological data have been measured since 1993 and these have enabled hydrological simulations to be carried out using the Shetran model for the period 1993-2011. The results from this work show that after ploughing there was an increase of around 50-100 mm in annual streamflow compared with the original upland grassland vegetation. However, the mature trees now show a decrease of around 250-300 mm in the annual streamflow compared with the original vegetation and a decrease of around 350 mm in the annual streamflow compared with when the site was ploughed. The simulation results show very clearly the non-stationary nature of the catchment during 1993-2011 with an annual increase in intercepted evaporation and a decrease in discharge as the trees grow. Simulation results also show that peak discharges are higher for a cover of smaller trees compared with taller trees. However, the results suggest that the bigger the event the smaller is the difference, i.e. there is absolute convergence for the two different tree scenarios at

higher discharges. The study shows how modelling can compensate for data deficiencies, to maximize outcomes. As a rare example of long-term analysis of non-stationary catchment behaviour it also provides real evidence of change that would otherwise have had to be inferred theoretically.

Highlights

- Coalburn is Britain's longest running forest hydrology research catchment
- Ploughing of the upland grassland caused a 50-100mm increase in annual streamflow
- The current mature forest has caused a decrease of 250-300 mm in annual streamflow
- The mature forest has reduced the size of the peak discharges
- The reduction in peak discharges is smaller for bigger precipitation events

1. Introduction

Experimental catchments are vitally important to understand the changes in hydrology as forests grow and develop. The two standard approaches to understand these changes are paired catchments or a long time series from a single catchment. In a standard paired catchment experiment two similar nearby catchments are selected, one is left unaltered and in the other there is a different or change in land-use (for example a forest is planted). The effect of the change in land-use can then be seen by comparing the discharges between the two catchments. This is a very powerful technique with the main problem being that two catchments can never be identical (e.g. they may have different soils) and so their response to a change in land-use will be different. A long time series from a single catchment can also be a powerful technique in understanding changes in discharge as a result of a change in land-use. The main problem here is that the meteorological data (and in particular the precipitation) is highly variable so it is difficult to understand which changes are caused by the change in land-use and which by the variations in the meteorological data. Hydrological models are useful in clarifying these changes. In this work a long time series from a single catchment is used.

When considering the effects of forestry on hydrology the standard questions that need answering are: how will it change the annual water yield, the baseflow and the peak flows? A review of changes in water yield resulting from paired experiments catchments can be seen in Brown et al. (2005). Other more recent comparisons include those of Brown et al. (2013), Peña-Arancibia et al. (2012) and Zhao et al. (2012).

There has also been a considerable amount of research carried out in South Africa and Australia considering the effect of forests on the annual water yield for both pine and eucalyptus forests (Scott and Prinsloo 2008; Webb and Kathuria 2012; Webb et al. 2012). Farley et al. (2005) have carried out a general review of the effects of afforestation on water yield.

The effect of forestry on changes in peak flows and baseflows was considered by Robinson et al. (2003) for a number of European catchments. O'Connell et al. (2007) considered the effect of land use change on peak flows, stating that the only way that evidence can be generated is to undertake actual catchment experiments. Other recent studies considering the effect of land-use change on peak flows include those by Wheeler and Evans (2009) and Pattison and Lane (2012).

In the UK the most important forest research catchments are those are at Plynlimon (Hudson et al., 1997; Robinson and Dupeyrat, 2005; Robinson et al., 2013), Balquhidder (Gustard and Wesselink, 1993; Calder, 1993; Johnson 1995) and Coalburn (Robinson, 1998; Robinson et al., 1998). Coalburn is the longest running and it provides a unique dataset for looking at the long-term effects of forestry on hydrology. The experiment started in 1967 when the 1.5-km² catchment was instrumented and the boundary defined. In 1972/73 the site was ploughed and planted. Since then the trees have grown and they have now reached maturity. Previously, Robinson (1998) looked at the changing hydrological response in the first 30 years of the Coalburn experiment. Archer and Newson (2002) and Archer et al. (2010) have looked at some of the more recent changes in discharge at the Coalburn catchment.

The overall aim of this work is to extend the analysis previously carried out for the Coalburn catchment, making full use of the unique 45-year dataset over the entire cycle from the original upland grassland vegetation, through ploughing the catchment and the forest growth up to mature trees. Using both the

measured data and hydrological modelling the work looks at changes in water yield, baseflow and peak flows over this non-stationary cycle. This provides a crucial insight into the effect of forest growth on the hydrology of an upland UK catchment. More generally, examples of long-term analysis of non-stationary catchment behaviour are rare and it is therefore expected that the study will provide real evidence of changes that would otherwise have had to be inferred theoretically and possibly erroneously. An additional aim is to demonstrate the complementary use of field data and model application to maximize analysis outcomes, with the modelling compensating for deficiencies in the data.

2. Coalburn Catchment, Meteorological Data and the Shetran Model

2.1 Coalburn catchment

Coalburn is located in the North of England, UK, within Kielder forest, about 40 km north-east of Carlisle. It is a 1.5km² catchment (Figure 1) in the headwaters of the River Irthing and varies in altitude from 270 m to 330 m AOD. The ground generally has low slopes with blanket peat (0.3 m – 3 m thick) covering 75% of the catchment and peaty gleys the remainder. This is underlain by boulder clay deposits (up to 5m thick) so the catchment is considered to be watertight.

Before research started on the catchment, the land was used as rough grazing for sheep with some overgrown and unused shallow ditches (Robinson et al. 1988). The main vegetation types were *Molina* grassland and peat bog species including *Eriophorum*, *Sphagna*, *Juncus* and *Plantago*. The first stage of using this as a research catchment was to define the catchment boundary. Two parallel boundary ditches were cut in early 1967 following the natural divide as closely as possible. Measurements then began while the catchment was left in its unaltered condition before forestry work started. In the summer of 1972, over around 90% of the catchment, open ditches were cut every 4-5 m; these ditches were around

0.8-0.9 m deep and 0.5 m wide. This gave a drainage network of 200 km/km² (60 times greater than the original network). The ditches have gradually filled in and are now only around 0.3 m deep due to sedimentation and leaf litter. The soil from the ditches was piled up at the side and Sitka spruce (*Picea sitchensis*) conifer trees were planted in spring 1973. The trees were about 0.2m tall and were planted at about 1.5 -1.7m spacing on the ridges. Average tree heights were around 1 m in 1978, 3m in 1985, 7m in 1992 and 9m in 1996 (Robinson et al., 1998). The estimated mean height was around 15m in 2010. In 1992 about 60% of the forest canopy had reached closure by 1996 the entire canopy had reached closure. 1996 data gives a forest yield of 10-12 m³ ha⁻¹ year⁻¹ timber growth. The plan is to start gradually harvesting the trees over about 10 years beginning in 2015.

2.2 Precipitation data

The precipitation data used in this work consist of monthly values from 1/1/1967 to 31/12/1992 and hourly values from 1/1/1993 – 31/12/2011 (Table 1). A considerable amount of effort has been taken to obtain consistent and reliable values across these 45 years. Originally 13 precipitation storage gauges were installed around the Coalburn catchment; these were reduced to 4 in 1972 and these 4 gauges were used to calculate the Thiessen weighted catchment monthly precipitation from 1967 to 2003 (Robinson et al., 1998; Robinson, personnel communication). A global 5% increase was then applied to these gauges (Robinson, 1998; Robinson et al., 1998) to account for wind effects (based on comparison with ground-level gauges). However, it is recognized that wind effects are not uniform through the year and that the correction is in error in snowy periods.

In 1992 a Tipping Bucket Raingauge (TBR) was installed by the Environment Agency of England and Wales at precipitation storage gauge site 12 near the outlet of the catchment. Comparison between the aerially averaged monthly precipitation and the TBR over the coincident period (1992-2003) shows that the TBR gave an overall 9% lower precipitation than the areal average of the storage gauges. This 9% difference appears to be due to two effects. Firstly, the effect of the raingauge type, with the monthly

storage gauge at the same location measuring 3.5% more precipitation than the TBR. Secondly, the location of gauge 12, which underestimates the areal averaged precipitation by 5.5%. Robinson et al. (1998) note that station 12 had a relatively low precipitation catch compared with other storage gauges and it was suggested that the combination of prevailing wind and local topography was the reason for this. So overall the TBR values were increased by 9% so that they were consistent with the monthly storage precipitation and then by an additional 5% to account for the wind effects. This means the monthly and annual totals are consistent with those in (Robinson, 1998; Robinson et al., 1998). It is important to note that this is a long-term average correction which may not be correct at the instantaneous or precipitation event scale.

The hourly TBR data have some small periods with missing data (Table 1). These have been infilled using other nearby hourly precipitation data. The data for 18/11/2009 - 4/12/2009 and 3/3/2010 - 24/3/2010 were infilled from a TBR at Spadeadam, which is located 12 km to the south-west of the Coalburn catchment outlet. Analysis of coincident data showed values on average 3% higher at Coalburn compared with Spadeadam and this correction factor was applied to the Spadeadam data. The data for 02/08/2010 - 4/10/2010 were infilled from a temporary Newcastle University TBR at The Flothers, which is located 1.5 km to the south of the Coalburn catchment outlet. In this case a 26% correction factor was applied to the Flothers data, to account for the considerably higher values found at Coalburn compared with The Flothers. The low values at The Flothers are thought to be due primarily to the exposed and thus very windy nature of the site.

The main errors in the precipitation dataset are due to snowfall. The storage gauges and TBR gauges both underestimate falling snow because of wind turbulence deflecting snowflakes across the rim of the gauge and as a result of un-melted snow being blown out of the gauge. Data from Eskdalemuir (45 km to the north-west) shows on average around 30 days of lying snow per year.

Average annual (1967-2011) precipitation at Coalburn is around 1400 mm, precipitation amounts being slightly lower in April and May and higher from October through to January.

2.3 Discharge data

A compound crump weir was installed at the outlet of the Coalburn catchment in 1966. This was replaced in 1991 due to leakage problems which resulted in some poor/missing data prior to 1991 (Table 1). A new central thin plate V notch within a non-standard broad crested weir was installed in August 1991. The original weir used a theoretical rating curve and there was good agreement between this and the gauged discharges. The new weir also uses a theoretical rating curve and excellent agreement has been found between these and the gauged flows (Robinson et al., 1998). In this work the data have all be converted to mean hourly discharge and the missing data periods are shown in Table 1. There are long gaps between 22/10/1972- 11/7/1973 and 18/6/1990 – 1/7/1991 but the remaining gaps are all less than two weeks. Overall there are nearly 45 years of consistent hourly discharge data.

2.4 Potential Evaporation data

An automatic weather station (AWS) was installed at Coalburn in 1971 but owing to the remoteness of the site and problems with the equipment there are a considerable number of gaps in its data. The Eskdalemuir weather station is located 45km North-West of Coalburn at a similar elevation. Data from this location were used for comparison with the AWS at Coalburn and to infill the missing data. After a considerable amount of analysis (due to gaps and changes in instrumentation at both sites), Robinson et al. (1998) have concluded that annual Penman potential evaporation during 1967-1996 at Coalburn was about 3% higher than the annual Penman potential evaporation at Eskdalemuir.

Hourly potential evaporation has been calculated for this work for 1992-2011 using the Penman-Monteith reference crop evaporation, ET_0 (Allen et al., 1998), using data from Eskdalemuir. The average ET_0 value for 1992-1996 was 459 mm and this compares well with the 454 mm for this period calculated by Robinson (1998), with a difference of around 1%. This difference is considered to be small enough

(compared with other errors) for no correction factor to be applied. Therefore, an annual time series of ET_0 was obtained for 1967-2011, using the Robinson (1998) Penman potential evaporation values up to 1992 and the ET_0 values from Eskdalemuir for 1993-2011. This provides a consistent and reliable dataset for the water yield analysis.

2.5 Shetran

Shetran (<http://research.ncl.ac.uk/shetran/>) is a physically-based distributed modelling system for water flow and sediment and solute transport in river catchments (Ewen et al., 2000; Birkinshaw et al., 2010). It includes components for vegetation interception and transpiration, snowmelt, overland flow, variably saturated subsurface flow, river/aquifer interaction and sediment yield. Solutions to the governing, physics-based, partial differential equations of mass and momentum are achieved on a three-dimensional grid using finite-difference equations. There have been a variety of applications recently of using Shetran to simulate the effect of land-use change and, in particular, forestry on discharge (Bathurst et al., 2010; Bathurst et al. 2011b; Birkinshaw et al. 2011).

The most convenient way of visualizing Shetran is as a set of vertical columns (Figure 1c shows the columns for the Coalburn catchment), with each column divided into finite-difference cells. The lower cells contain aquifer materials and groundwater, higher cells contain soil and soil water and the uppermost cells contain surface waters and the vegetation canopy. The mesh follows the topography of the catchment with channels specified around the edge of the finite-difference cells (Figure 1c). The parameters of the physical laws vary from square to square on the mesh, thus allowing representation of the spatial heterogeneity of the physical properties of the rocks, soils and vegetation cover. The coupled surface/subsurface representation allows overland flow to be generated by precipitation excess over infiltration and by upward saturation of the soil column

Shetran is described as being physically-based as it solves the fundamental physics-based equations of mass, momentum and energy conservation. The model parameters therefore have physical meaning and can be evaluated from field measurements and physical reasoning. It is spatially distributed, which means that the input meteorological data, the model parameters and the output variables can vary between soil columns. The physically-based approach is important in this study as it allows the change in forest cover to be modelled by changing the vegetation parameter values using physical reasoning to represent the forest as it grows. The spatially distributed nature of the model is also important as some of the catchment remains un-forested and this can be included in the model.

In this work the analysis is focusing on how the growth of the forest affects the hydrology of the catchment. The crucial part is therefore calculating the interception and drainage of precipitation on the forest canopy, evaporation of intercepted water and transpiration from the forest. Interception of precipitation and drainage from the canopy are calculated in Shetran using the Rutter equation (a review of rainfall interception loss by forest canopies can be seen in Carlyle-Moses and Gash, J. H. (2011) and the different modelling approaches in Muzylo et al. (2009)). Evaporation from intercepted storage and transpiration are calculated in Shetran using the Penman-Monteith equation (Allen et al., 1998), in this case using meteorological data from the Eskdalemuir weather station. The aerodynamic resistance r_a (s/m) is calculated from the wind velocity using the logarithmic boundary layer equation (Allen et al., 1998). The canopy resistance r_c (s/m) is set to zero when the canopy is wet. Once all the water from the canopy is evaporated then transpiration takes place within the model using the specified canopy resistance. For transpiration for a short grass reference crop the canopy resistance is set to 70 s/m, the value for forests is often higher than this; in the Shetran model for the Coalburn catchment this value is calibrated.

In order to carry out a good simulation high quality meteorological data are necessary. For the Coalburn catchment the temporal resolution of the data for 1967-1992 is insufficient. Shetran simulations were therefore carried out only for the period from 1/1/1993 to 31/12/2011. It can be seen from Table 1 that hourly data are available for the whole of this period (with some gaps infilled as already indicated).

Although the parameters have physical meaning in Shetran it is necessary to carry out some calibration within plausible ranges in order to get a good match between the measured and simulated discharges. The classic method to achieve this is splitting the data into a calibration and a validation period. However, the Coalburn catchment is somewhat unusual, as the data analysis will show, in that the growth of trees in the catchment has a considerable effect on the hydrology of the catchment and so the catchment response can be considered to be non-stationary. The approach here is similar to that carried out in other catchments with different models (e.g. Post et al., 1996; Seibert and McDonnell, 2010). This is to carry out two split sample calibration/validations. The first calibration/validation uses the periods 1/1/1993-31/12/1996 for calibration and 1/1/1997 – 31/12/2011 for validation and the second calibration/validation uses the periods 1/1/2007 -31/12/2011 for calibration and 1/1/1993-31/12/2006 for validation. Details of the different calibrations are given in the results section but to account for the non-stationary catchment the only parameters changed were the aerodynamic resistance and canopy storage capacity (to account for the growth in tree height from an average of 8m in 1/1/1993-31/12/1996 to 15m in 1/1/2007 -31/12/2011) and the overland flow Strickler coefficient (inverse of Manning's roughness coefficient) (to account for the slower flow in the ditches as these have gradually filled in over time).

There are models available that include a biomass or forest growth component (e.g. Miehle et al. 2009 and Feikema et al. 2010) and in these models the need to carry out two split sample calibration/validations would be unnecessary. However, the lack of measured data about the forest growth and the ability of Shetran to be able to simulate the hourly water dynamics in the forest canopy (and also over the entire catchment) using the standard approach of the Rutter model and the Penman-Monteith equation makes it a suitable model for these simulations.

3. Data Analysis Results

3.1 Water yield

A comparison of annual precipitation, discharge and potential evaporation up to 1996 is given in Robinson et al. (1998). The results in Table 2 and Figure 2 are a direct extension of this work up to 2011. Robinson et al. (1998) found there was a marked increase in annual stream flow after the afforestation; which was contrary to the bulk of published results at the time, which show a significant reduction in flows due to forestry (e.g. Bosch and Hewlett, 1982). The initial increase can be seen in Table 2 where before ploughing the actual evapotranspiration losses were greater than the reference crop potential evapotranspiration losses but from 1972-1991 actual evapotranspiration losses were smaller. In Figure 2 the same effect can be seen, where precipitation is plotted on the x axis against discharge on the y-axis. The data before ploughing (1967-1971) are shown as black diamonds and for the first 20 years after ploughing (1972-1991) the data points are generally above the black diamonds, so for a particular precipitation the discharge is greater (and so actual evapotranspiration smaller) after ploughing than before. Robinson et al. (1998) suggested this increase in discharge is due to the extensive ploughing of the catchment carried out in 1972. They suggest that this caused a lowering of the water table, reducing evaporation losses, and the suppression of transpiration from the bare soil in the open drains and overturned turf ridges. Recent results carried out by other researchers analysing the effect of drainage ditches on both discharge and tree growth in peat soil have shown similar results both in the UK (Holden et al., 2011; Ballard et al., 2012) and worldwide (Koivusalo et al., 2008; Sarkkola et al., 2012)

Robinson et al. (1998) found that over time the bare soil in the drains became colonised with vegetation and the young forest plantation became established and grew. As a result the evaporation losses have increased, so that by around 1994 the evaporation losses have finally exceeded and the stream flow reduced compared to those of the original grassland. Since then the trend has continued and this can be seen very clearly in the results (Figure 2), where the data from all more recent years are well below the black diamonds from the years before ploughing, showing a greater evaporation loss and a lower stream

flow. The results in Table 2 show the actual evapotranspiration is now considerable larger than the reference crop potential evapotranspiration. So during 2007-2011 the annual average actual evapotranspiration was 747 mm compared with the reference crop potential evapotranspiration of 450 mm, a difference of 297 mm. This means that there is now annually around 350 mm more evapotranspiration compared with when the forest was ploughed and planted. There is also in the region of 250-300 mm more evapotranspiration than from the original grassland vegetation over the catchment. The runoff ratio (Table 2) shows a similar large change from around 70% after ploughing to around 55% in 2011.

The cumulative plot of water loss for the reference crop potential evapotranspiration, the actual evapotranspiration and the difference between the two since 1972 (Figure 3) also shows a similar trend. Up to around 1990 the actual evapotranspiration is less than the reference crop potential evapotranspiration and the cumulative difference between the two is increasing. However, since then the actual evapotranspiration is greater than the reference crop potential evapotranspiration so by 1997 the cumulative totals are similar. After 1997 the cumulative actual evapotranspiration is larger than the cumulative reference crop potential evapotranspiration and by 2011 the cumulative difference is around 3300mm.

The initial increase and then subsequent decrease in annual stream flow at Coalburn shows a much slower response to that seen in other countries. For example, Scott and Prinsloo (2008) in South Africa found that for a pine plantation the trees started to reduce the annual stream flow six years after planting. This is compared with around 22 years (1972-1994) after planting at Coalburn.

The reason for this massive increase in actual evapotranspiration in recent years can be seen in Table 3, which uses using the hourly Eskdalemuir data and the Penman-Monteith equation. This shows the reference crop potential evapotranspiration for the years 1993-2011 but also the potential intercepted evaporation and potential transpiration for grass ($h = 0.5$ m), small trees ($h = 8$ m) and tall trees ($h = 15$ m). Taller vegetation has a much lower aerodynamic resistance than short vegetation (see the logarithmic

boundary layer equation, Allen et al., 1998) and so tall trees together with a wetted canopy (which means the canopy resistance is zero) have very high intercepted evaporation totals (see the Penman Monteith equation, Allen et al., 1998). Thus the annual potential intercepted loss for a 15-m forest is 1712 mm compared with the reference crop potential evaporation total of 450 mm. The 1712 mm is obviously for a forest canopy that is continually wet so annual values will not approach this level but Calder (2005) showed that large interception losses of water from forest canopies are expected with low intensity precipitation in temperate climates. It is also interesting to note that annual potential transpiration losses for trees (with a higher canopy resistance, 120 s/m, than the reference crop, 70 s/m) are actually smaller than the reference crop potential evaporation totals.

3.2 Peak discharges

In general forests reduce the size of flood peaks compared with non-forested catchments. However, there is still a significant scientific debate on the issues. For example, Bathurst et al. (2011a) argue that the small/moderate peak discharges are reduced in forested catchments but for really big events there is a convergence in the peak discharges for forested and non-forested catchments. Birkinshaw et al. (2011) shows it depends on the soil depth with convergence for thin soils but no convergence for deep soils. Green and Alila (2012), on the other hand, argue that the bigger the discharge the larger the change in frequency of discharge events between forested and non-forested catchments. A recent discussion of these issues can be seen in Birkinshaw (2014) and Alila and Green (2014).

For the 45 years of measured discharge data in the Coalburn catchment there is no paired catchment with which to compare the data and carry out the sort of analysis found in Bathurst et al. (2011a) and Green and Alila (2012). In order to overcome this, Robinson (1998) examined peak flows before and after ploughing using a unit hydrograph approach. He found an increase in peak discharges and a reduction in time to peak following ploughing. More recent changes in peak discharges as a result of different tree heights are considered in the Shetran modelling work in Section 4. In this section the analysis of trends in

the data is considered and this is carried out using the Mann-Kendall test (Kendall 1975). This is a non-parametric test that has been used in a number of other hydrological studies to detect changes in regimes (Lettenmaier et al., 1994; Déry and Wood, 2005). Only trends with $p < 0.05$ are considered to be statistically significant.

Before we consider the peak discharges it is worth considering the annual totals. Data for 1967-2011 are shown in Figure 4, with the years 1972, 1973, 1990 and 1991 removed because of missing discharge data. Annual precipitation shows a statistically significant upward trend in time, with $p = 0.0002$ and a slope of 10.2 mm/year. This implies that annual precipitation totals are in the region of 450 mm higher in 2011 compared with 1967. However, no statistically significant trends were found in the annual discharge totals or the annual reference crop evapotranspiration total. The annual maximum discharge varies from 2.25 mm/hr or 0.94 m³/s (1/4/1992) up to 12.89 mm/hr or 5.37 m³/s (30/8/1975). No statistically significant trends were found in the annual maximum discharge time series. The number of peaks over a threshold of 2 mm/hr varies from 11 in 1984 to 1 in both 1999 and 2006. No statistically significant trends were found in this time series or time series with other threshold values. As the trees grow and the annual actual evapotranspiration increases, a decrease in annual discharge and of flood peaks might be expected but in this instance this is not occurring. It seems that the increase in actual evapotranspiration is compensated for by an increase in precipitation, resulting in no significant change in the discharge regime.

3.3 Flow duration curve and base flows

In previous sections we have considered the change in water yield and peak discharges as the forest grows. In this section we are considering the change in the flow regime as characterized by the Flow Duration Curve (FDC) and the Base Flow Index (BFI). The flow duration curve shows the percentage of flow in a stream that is likely to equal or exceed a specified value. In this case it is derived from hourly values and the results from 5 years before ploughing and for four 10-year periods (i.e. a total of 40 years)

post ploughing can be seen in Figure 5. The thicker black line shows the FDC before ploughing in the 1967-1971 period. After that there appears to be a trend with generally higher medium and low flows in the period from 1972-1991 compared with 1967-1971. From 1992 onwards these medium and low flows are lower than the 1972-1991 flows and more similar to the 1967-1971 flows.

Analysis of the trend in the FDC can be seen by following the procedure in Zhang et al. (2008) and Sawicz et al. (2011) and considering the slope (S_{FDC}) of the FDC between the 33rd and 66th percentiles on a semi-log scale (as this represents a relatively linear part of the FDC curve):

$$S_{FDC} = \frac{\ln(Q_{33\%}) - \ln(Q_{66\%})}{(0.66 - 0.33)} \quad \text{Eqn. 1}$$

Table 4 shows the value of the slope is 4.59 before ploughing; this reduces to 3.30 in the 10 years following ploughing and then increases back to 4.63 in the most recent 10 years. The ploughing of the catchment seems to have had a major effect on the FDC, increasing the medium and low flows. Since then, as the trees have grown, the evapotranspiration has increased and this has reduced the medium and low flows. Lane et al. (2005) have also considered the effect of afforestation on the FDC, including a method to remove the variability in the rainfall signal, leaving changes in stream flow solely attributable to the evapotranspiration of the plantation. They found the reduction in the FDC depended on the catchment type.

A standard method of considering low flows is the BFI (Gustard et al., 1993). The BFI may be thought of as a measure of the proportion of the river runoff that derives from stored sources. Robinson (1998) found an increase from around 0.1 before ploughing to around 0.2 after ploughing with a gradual decline as the forest grew. The extension of these data to 2011 (Figure 6) shows the declining trend continuing with a

typical BFI value since 2007 of around 0.15. As with the FDC the tree growth and corresponding increase in evapotranspiration is causing a change in the BFI.

The difficulty of interpreting either the FDC or the BFI values is that the changes since ploughing in 1972 have taken place whilst the trees are growing but also during a period of increasing precipitation (Section 3.2). It is therefore hard to separate the two forcing agents and reach a definite conclusion on how much the changing shape in the FDC and changes of values in the BFI can be attributed to the growing forest.

3.4 Recessions

A method of avoiding the problem of changing precipitation over the 45-year catchment experiment is to consider the hydrograph recessions. By considering only the recessions the effect of the changing precipitation on the catchment can be ignored. There has been a considerable amount of research recently considering hydrograph recessions (e.g. Kirchner, 2009; Krakauer and Temimi, 2011). In those examples the change in discharge in each hour is plotted against the discharge but only for periods in which precipitation and evaporation are small. In this work, although hourly discharge is available for the full 45 years (1967-2011), hourly precipitation and potential evaporation are available only more recently (1993-2011). To obtain a consistent recession record over 45 years the discharge hydrograph was examined. Firstly, any recessions in the hourly discharge time series longer than 24 hours were extracted (where a recession is considered to be a fall from the discharge in one hour to the discharge in the next hour), so the data considered are only for periods in which there is low precipitation. Secondly, the first four hours of the recession data were removed, as these depend more on the surface runoff which is affected by the type of precipitation. Thirdly, for every hour the discharge (Q) was plotted against the change in discharge in that hour (\dot{Q}) (Figure 7). In effect the discharge is a surrogate for the storage so the plot is the change in discharge for a particular storage. As would be expected as the catchment dries out (a lower

storage and discharge) the change in discharge becomes smaller (this is approaching the tail of the hydrograph). There are some outliers in Figure 7. The outliers that give a large \dot{Q} for a particular value of Q are due to snowmelt events and those with a small \dot{Q} for a particular value of Q are where some precipitation has occurred but not sufficient to give an increase in discharge; if the precipitation had increased the discharge the data points would **not** be extracted from the discharge record and so would not be shown in the figure. The higher flows (greater than 1mm/hr with a % exceedance of around 1%) are not shown in Figure 7, as there are insufficient data above discharges of 1 mm/hr to show any trends. The figure shows a considerable amount of scatter for the actual point values but the trend is very clear. After ploughing in 1972, \dot{Q} is smaller for most discharges (<0.75 mm/hr) than before ploughing, but higher for the larger discharges. For say a discharge of 0.2 mm/hr, the ploughed catchment has a smaller \dot{Q} of -0.011 compared with -0.017 for the unploughed catchment, which means that the recession is more gradual. As Robinson (1998) suggests the flow from the soil into the drains is lowering the water table around the drains and sustaining the low flows, making the recession more gradual. From 1972 onwards \dot{Q} gradually becomes smaller for the higher discharges but it stays the same at lower discharges, which is what would be expected with the higher evapotranspiration as the trees grow making the soils generally drier. The most striking observation from Figure 7 is that the ploughing of the catchment has had a significant effect on flows less than 0.2 mm/hr and after 40 years this effect can still be seen. It is interesting to note that Holden et al. (2011) found a similar result when looking at restoring blanket peat, in that water table dynamics may not function in the same way as those in undisturbed blanket peat even many years after management intervention.

4. Shetran Simulation Results

Shetran does not have a vegetation growth component, therefore two calibration/validation scenarios were carried out (Table 5) to account for non-steady conditions as a result of tree growth in the catchment. Scenario 1 corresponds to the average tree height (8 m) in 1993-1996. Scenario 2 corresponds to the average tree height (15 m) in 2007-2011. The taller trees in scenario 2 give an increase in the evapotranspiration and a decrease in the discharge. Around 10% of the catchment is covered in upland grassland and the parameter values for this area were left unaltered between the two scenarios.

4.1 Calibration Parameters

As Shetran is a physically-based model the parameters were based as far as possible on values measured in the catchment or typical literature values. However, some of the parameters were calibrated to improve the fit between the measured and simulated discharges and it is impossible to validate all of these (in particular it is hard to validate the vegetation parameters and so validate the results of the simulations showing the partitioning between intercepted evaporation and transpiration).

In Shetran canopy interception and drainage is simulated using the Rutter equation (Rutter et al., 1972). The Rutter interception and drainage parameters are often difficult to obtain; however, during 1994 and 1995 field interception experiments were carried out for two stands of trees in the Coalburn catchment (Robinson et al., 1998) and for some of these events a Rutter model was calibrated. The canopy drainage parameters for the trees in scenario 1 are based on these calibrated parameters. The canopy storage capacity values for the trees in scenario 1 were calibrated but are within the range of values from the interception experiments. The canopy storage capacity for tall trees in scenario 2 and for the grassland was calibrated but is similar to values used by the UK Meteorological Office MORECS system (Hough and Jones, 1997). The canopy storage capacity and the leaf area index for conifer trees both increase in the summer and reduce in the winter (Rautiainen et al., 2012), and time varying values were incorporated into the dataset to account for this. Table 6 shows there is a significant increase in the canopy storage capacity from grassland (0.1 – 0.8 mm) to small trees (0.5 – 1.0 mm) to large trees (1.5 – 3.0 mm), it can

also be seen that the seasonal variation for the grassland is much larger compared with the coniferous forest. The leaf area index is based on measured values from other catchments collated by Breuer et al. (2003). The aerodynamic resistance was based on the measured tree heights and the time varying wind speed using the logarithmic boundary layer equation (Allen et al., 1998). The higher the wind speed the lower the aerodynamic resistance and the higher the potential evapotranspiration. At Coalburn the average wind speed is 2.8 m/s and using this value the average aerodynamic resistances can be seen in Table 6. The lower aerodynamic resistance for tall trees compared with small trees and grassland can clearly be seen.

The Strickler overland flow was calibrated for scenario 1 and scenario 2. In scenario 1 the value was 1.6 ($\text{m}^{1/3} \text{s}^{-1}$) and in scenario 2 it was 1.2 ($\text{m}^{1/3} \text{s}^{-1}$). These are typical values (Bathurst et al. 2011b) for the Strickler coefficient and the reduction over time (increased roughness) is a result of the drainage ditches having partially filled in as a result of sedimentation and leaf litter, so a lower value for the scenario 2 is expected.

The main soil type in the Coalburn catchment is blanket peat (0.3 m – 3 m thick) covering around 75% of the catchment, with peaty gleys covering the remainder. The shallow upper peat layer (called the acrotelm) consists of poorly decomposed organic matter with a relatively large pore structure and high saturated conductivity, the deeper layers (called the catotelm) have smaller pore spaces and low saturated conductivity (Ingram, 1978; Holden et al., 2011). There are insufficient data on the spatial distribution of peat depth over the catchment to include it in the model so the average 1.2-m deep peat soil was applied everywhere and this was split into 4 different layers. The shallower layers (acrotelm) have a high conductivity with lower values in each subsequent layer (Table7). The conductivities of the top two layers were calibrated, with the conductivity in each subsequent layer reduced by a factor of 10. The remaining parameters for the peat were based on laboratory measurement of peat (Schwärzel et al., 2006). The catotelm layer actually has very little effect on the hydrology of the catchment as the soils have a very

low conductivity and so are generally saturated the whole time, the hydrological response then depending on the parameters in the top active acrotelm layers.

So overall between the two scenarios the soil parameters remain unaltered but the vegetation parameters show a decreasing aerodynamic resistance and increasing canopy storage capacity for tall trees compared with small ones and there is a small reduction in the Strickler overland flow coefficient.

4.2 Time Series and Mass Balance Results

The overall results of the 19-year Shetran simulation for both scenarios can be seen in Table 8. For scenario 1 in the calibration period (1993-1996) the comparison between the hourly measured and simulated discharges gives a Nash Sutcliffe Efficiency (NSE) of 0.91 and similar mean measured and simulated discharges. In the validation period the trees are taller but the vegetation parameters for the small trees are still used in the model. This means that the actual evapotranspiration is greater and the discharge lower, whereas in the model the basis for determining the evapotranspiration and discharge remains unchanged. The result can be seen in the reduction in the ratio of the measured discharge to the simulated discharge from 1.04 in 1993-1996 (calibration period) to 0.83 in 2007-2011 (validation period). As the simulated discharge is too high in 2007-2011, the NSE, as would be expected, shows a drop compared with the calibration period (0.91 to 0.82).

Scenario 2 was calibrated for the period from 2007-2011 with different vegetation parameters to reflect the taller trees. The mean measured and simulated discharges are therefore similar for 2007-2011 and when comparing the hourly measured and simulated discharges the NSE is 0.91. For the earlier (validation) period the trees in reality are smaller and so there is less evapotranspiration and higher discharges compared with the model. This can be seen in the increase in the ratio of the measured discharge to the simulated discharge from 0.97 in 2007-2011 (calibration period) to 1.27 in 1993-1996

(validation period). As the simulated discharge is too low in 1993-1996, the Nash-Sutcliffe efficiency, as would be expected, shows a drop compared with the calibration period (from 0.91 to 0.86).

Similar results can be seen in Figure 8 which shows the maximum daily discharge for both scenarios plotted against the measured discharges. In Figure 8a for 1993-1996, the simulated discharges for scenario 1 are similar to the measured values whereas the simulated discharges for scenario 2 are too small as the trees are taller than the values used in the simulation and so there is too much evapotranspiration. In Figure 8b for 2007-2011 the opposite response can be seen, with the simulated discharges for scenario 2 similar to the measured values whereas the simulated discharges for scenario 1 are too large (as the trees used in the simulation are too small).

The simulated and measured time series for the major event in January 2005 can be seen in Figure 9. This is the second largest measured discharge in the 1993-2011 period. The figure shows the excellent correspondence between the simulated and measured discharges with the peaks and the recessions all well matched. Generally the simulated peaks are too high in scenario 1 as the trees in 2005 have grown considerably compared with the simulated 8 m.

The changing hydrological response of the catchment over the period from 1993-2011 can be seen in more detail in Figure 10. This shows the annual measured and simulated discharges for both scenarios (Figure 10a) and the ratio of the measured to the simulated discharge (Figure 10b). These show very clearly the non-stationary catchment response as the trees are growing on the catchment, increasing the evapotranspiration and reducing the discharge. In scenario 1 the simulated and measured discharges are very similar in 1993-1996 so the measured/simulated discharge ratio is approximately equal to 1.0 but after that there is a gradual reduction in the ratio to around 0.8 by 2011. Conversely, in scenario 2 the measured/simulated discharge ratio starts around at around 1.2 in 1993-1996 and drops to less than 1.0 by 2011.

The simulations show that the reason for the reduction in discharge in scenario 2 compared with scenario 1 is due to the increased intercepted evaporation from the forest canopy. This annual loss has increased in

the simulation from 308mm to 448mm due to the higher canopy storage capacity and the lower aerodynamic resistance for the taller trees increase the intercepted evaporation. The transpiration and bare soil evaporation are very similar for the two scenarios. The question that arises is whether these results reflect the actual losses in the catchment. As stated earlier, though, interception experiments were carried out at the Coalburn catchment from May 1994 to December 1996 so the simulated interception losses can be compared with the measured losses. In the experiment two sites were chosen and large plastic sheets were installed to collect all stem flow and net-precipitation and hence calculate interception losses. At one site there were 7-m tall trees and the other had 9-m tall trees. Overall in this period, the interception loss was 24.9% of the gross precipitation for the 7-m trees and 27.7% for the 9-m trees. The simulated interception loss for this period for scenario 1 with 8-m trees is 22% of the gross precipitation. However, the interception experiment did not include the non-forested part of the catchment (10%) and areas with small trees were also specifically not included. By contrast, the Shetran simulation is the areal average including grassland areas and areas with smaller trees. So for the trees where the interception experiment was carried out the intercepted losses from Shetran will be similar to the measured losses. The areal averaged intercepted losses for scenario 2 (15-m trees) over the same period are 32% of precipitation. So the simulation suggests that for the taller trees an extra 10% of the precipitation is lost as intercepted evaporation. For mature forested areas in the UK (i.e. excluding the non-forested part of the catchment) this is within the range of values given by Calder (1990) and the UK Forestry Commission (Forestry Commission 2005). So overall the simulation results correspond well with the measurements and expected interception losses at this upland UK location.

4.3 Peak discharges

The calibration of Shetran for two different scenarios corresponding to different tree heights means that the results of tree growth on peak discharges can be analysed. Both scenarios have a time series of 19 years of hourly discharge for the same meteorological data.

One method of analysing the results is to compare the maximum daily discharges from the two scenarios for each corresponding day of the 19-year simulations (Birkinshaw et al., 2011). The discharge from scenario 2 (tall trees) is shown on the x-axis and from scenario 1 (small trees) on the y-axis (Figure 11). This type of analysis is sometimes called Chronological Pairing (CP), where the results give a direct comparison of the discharge from the same meteorological event. As would be expected the small trees in scenario 1 yield, in general, larger discharges than the tall trees in scenario 2. In some cases there are points below the line of equality and these are due to the shallower recessions (as a result of a lower Strickler overland flow coefficient) found in scenario 2, so although the peak discharge was greater in scenario 1 this has dropped more rapidly than in scenario 2. Figure 11 shows there can be a range of discharges for scenario 1 (small trees) for a given discharge in scenario 2 (tall trees), e.g. in scenario 2 a discharge of $0.5 \text{ m}^3/\text{s}$ can have a scenario 1 discharge between $0.45 \text{ m}^3/\text{s}$ and $1 \text{ m}^3/\text{s}$. The range depends on the initial conditions and the type of precipitation (Birkinshaw et al., 2011). However, the range seems to get somewhat smaller for the higher discharges. The 50th percentile (together with the 5th and 95th percentiles) shows an increase in the difference between scenario 2 and scenario 1 for events from zero up to $0.5 \text{ m}^3/\text{s}$ but after that the line becomes nearly parallel to the line of equality, with a slight decrease towards the end of the line (there are insufficient data after this to plot the line). So the data appear to show that the smaller trees allow an increase in the peak discharge compared with tall trees and for larger events this effect is slightly less.

An alternative method of showing the effect of the two scenarios on discharge (Green and Alia, 2012) is the Frequency Pairing (FP) approach (Figure 12). Annual maxima are extracted for both scenarios from the 19-year simulations and each series is ranked and plotted on a flood frequency plot. In this the x-axis shows the return period (years) of an event and the y-axis the event discharge. There are therefore two sets of points, one for scenario 1 and one for scenario 2. The discharges for scenario 1 (small trees) are higher than for scenario 2 (tall trees) for a particular return period. It is important to note that as the events are all ranked, the discharges for a particular return period generally correspond to different years

between the two scenarios. Comparing the two scenarios by comparing events with equal return period, the L-moments show parallel lines for lower annual maximum discharges (return periods from 1.2 to 5 years) but for return periods bigger than 5 years the lines converge. So for the bigger annual maximum events (e.g. 25-year event) there is less difference between discharges than for the smaller annual maximum events (e.g. 2-year event), i.e. there is absolute convergence for the two different scenarios at higher discharges. So for a particular precipitation event the smaller trees will have a bigger discharge but the bigger the event the less the difference in discharges between the smaller and taller trees. Although soils in the Coalburn catchment are simulated as being 1.2 m deep only the top layers of peat (acrotelm) are active and so these results correspond with the shallow soil scenario in Birkinshaw et al. (2011) for which absolute convergence between the discharges for a forested and logged catchment was found.

Another way of looking at the same data, which is favoured by Green and Alila (2012), is to consider the changes in flood frequency. Thus an event with a return period of 5 years ($2.1 \text{ m}^3/\text{s}$) for scenario 2 (tall trees) becomes an event with a return period of 3.2 years for scenario 1 (small trees). For bigger events an event with a return period of 10 years ($2.3 \text{ m}^3/\text{s}$) becomes an event with a return period of 6.5 years and an event with a return period of 20 years ($2.6 \text{ m}^3/\text{s}$) becomes an event with a return period of 13 years. So there is an increase in frequency of approximately 50% for all these events. As Green and Alila (2012) point out, the increase in frequency for the larger magnitude floods is due to the highly nonlinear relation between flood frequency and magnitude (i.e. there is a highly non-linear x-axis, so a small increase along the x-axis produces a large increase in return period for big events) which creates increases in frequency for floods in the upper tail of the distribution even when the fitted L-moments appears to be converging.

5. Discussion and Conclusions

Coalburn is the longest running forest research catchment in the UK and it provides a unique dataset for looking at the long-term effects of forestry on hydrology. Research at the site started in 1967 when the 1.5 km² catchment was instrumented and the boundary defined. In 1972/73 the site was ploughed and planted. Since then the trees have grown and they have now reached maturity. In this paper there has been extensive analysis of the 45-year measured dataset and also detailed hydrological modelling of the most recent 19 years of higher resolution data. The work shows how the analysis of the field data can be complemented and extended by modelling to overcome the limitations imposed by the data. This is particularly important for this catchment as there has been a trend of increasing precipitation over the 45 years experiment and in the analysis of the field data it is often difficult to separate the effects of the growing forest from the increasing precipitation. To keep the modelling work simple and easy to understand the simulations do not consider any parameter uncertainty. Future work is planned considering ensembles of feasible parameters and this should provide insights into the effect of parameter uncertainty on the simulated results.

The main conclusions of the research are as follows:

- After the afforestation there was initially a marked increase of around 50-100 mm in annual streamflow. This was a result of the extensive deep ploughing of drainage ditches in the peat soil before the trees were planted.
- The mature trees have produced a decrease of around 250-300 mm in the annual streamflow compared with the original upland grassland vegetation and a decrease of around 350 mm in the annual streamflow compared with when the site was ploughed and the trees planted.
- Simulation results show that the decrease in discharge for the mature trees is due to the increased interception evaporation from the forest canopy. The areal averaged interception loss increased from 22% of the gross precipitation in 1993-1996 to 32% in 2006-2011.

- Ploughing of the catchment changed the shape of the hydrograph recessions and 40 years later the recessions have still not reverted to their original shape.
- The simulation results show very clearly the non-stationary nature of the catchment from 1993-2011 with an annual increase in evapotranspiration and a decrease in discharge as the trees grow.
- The ploughing in 1972/73 caused an increase in peak discharge and a reduction in the time to peak.
- Simulation results show that peak discharges are higher for smaller trees compared with taller trees. However, the results suggest that the bigger the event the smaller the difference, i.e. there is absolute convergence for the two different scenarios at higher discharges.
- Simulation results also show for large discharge events there is an approximately 50% increase in the frequency of a given discharge for a cover of smaller trees compared with taller trees

These conclusions have important implications for the analysis of catchments under a changing climate. If droughts are considered to be a major risk, the significant reduction of annual streamflow under mature forests is important. For the opposite case of flooding, many political commentators are advocating planting trees in the upland part of catchment to reduce the flooding risk downstream. The increase in peak discharges as a result of ploughing and then the subsequent decrease in discharge as the forest grows therefore have important implications. These conclusions are directly applicable only to typical upland UK catchments with high precipitation on peat soils which are saturated most of the time. Nevertheless, as a rare example of long-term analysis of non-stationary catchment behaviour, the study also provides real evidence of change that would otherwise have had to be inferred theoretically, and possibly erroneously. It may therefore hold more general lessons for studies elsewhere.

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Table 1

Meteorological datasets used in this work. Additional information and comparison between the coincidental data is given in the text.

Data Type	Data Period	Location of data	Data Frequency	Notes
Precipitation	1/1/1967 – 31/12/1992	Coalburn	Monthly	4 storage gauges
Precipitation	1/1/1993 – 31/12/2011	Coalburn	Hourly	UK Environment Agency Tipping Bucket Raingauge. Missing data for 18/11/2009 - 4/12/2009 and 3/3/2010 - 24/3/2010 infilled from Spadeadam and for 02/08/2010 - 4/10/2010 infilled from The Flothers.
Discharge	1/1/1967 – 31/12/1992	Coalburn	Hourly	Missing data for 22/10/1972- 11/7/1973 , 21/12/1974 - 4/1/1975, 1/10/1981- 13/10/1981, 5/12/1985 – 16/12/1985, 18/6/1990 – 1/7/1991 , 4/12/1991 – 16/12/1991 Data gaps greater than two weeks are shown in bold.
Potential evaporation	1/1/1967 – 31/12/1992	Coalburn and Eskdalemuir	Annual	Penman potential evaporation calculated using a mix of the Coalburn and Eskdalemuir AWS data
Potential evaporation	1/1/1993 – 31/12/2011	Eskdalemuir	Hourly	Penman Monteith Reference Crop evaporation (ET ₀)

Table 2

Water balance of the Coalburn catchment showing annual average values (mm) over five-year periods, where P is the precipitation, Q is the discharge, AE is the actual evapotranspiration (calculated from $P - Q$) and ET_0 is the reference crop potential evapotranspiration

	P	Q	AE	ET_0	$ET_0 - AE$	Runoff ratio(%)
Before ploughing						
1967-1971	1266	793	472	433	-39	62.6
After ploughing						
1972-1976	1149	766	383	435	52	66.7
1977-1981	1421	995	426	437	11	70.0
1982-1986	1445	1025	420	442	22	70.9
1987-1991	1415	998	416	439	23	70.5
1992-1996	1370	846	524	454	-70	61.8
1997-2001	1526	926	600	438	-162	60.7
2002-2006	1498	826	672	456	-216	55.1
2007-2011	1651	904	747	450	-297	54.8

Table 3

Potential annual evapotranspiration totals (mm). Note that these results come directly from applying the Eskdalemuir meteorological data to the Penman-Monteith equation. h is the vegetation height which changes the aerodynamic resistance.

Year	Reference crop potential evaporation ($r_c = 70$ s/m)	Potential intercepted loss ($r_c = 0$ s/m)				Potential transpiration losses ($r_c = 120$ s/m)		
		$h = 0.12$ m	$h = 0.5$ m	$h = 8$ m	$h = 15$ m	$h = 0.5$ m	$h = 8$ m	$h = 15$ m
1993	413	740	1332	1680	337	322	318	
1994	439	812	1497	1898	357	345	342	
1995	530	907	1627	2049	443	434	433	
1996	459	793	1418	1785	379	369	367	
1997	454	747	1286	1601	380	364	359	
1998	409	713	1270	1596	336	321	317	
1999	454	786	1409	1773	376	363	361	
2000	433	744	1313	1648	357	343	339	
2001	438	736	1261	1569	360	338	332	
2002	427	713	1211	1502	351	329	323	
2003	472	793	1406	1765	395	390	390	
2004	472	796	1379	1721	389	369	365	
2005	437	768	1417	1798	365	366	368	
2006	473	805	1466	1854	400	403	404	
2007	444	761	1355	1704	368	356	353	
2008	436	750	1329	1670	360	345	341	
2009	449	760	1317	1644	369	352	348	
2010	485	810	1399	1746	401	382	378	
2011	435	711	1226	1522	349	331	324	
Average	450	771	1364	1712	372	359	356	

Table 4

Slope of the flow duration curve (S_{FDC}) between the 33rd and 66th percentiles before ploughing and for ten-year periods after ploughing

	$S_{FDC} (-)$
Before ploughing	
1967-1971	4.59
After ploughing	
1972-1981	3.30
1982-1991	3.98
1992-2001	4.12
2002-2011	4.63

Table 5

The two scenarios for calibration/validation of the Coalburn catchment

Parameter	Calibration	Validation
Scenario 1 – small (8 m) trees	1/1/1993-31/12/1996	1/1/1997 – 31/12/2011
Scenario 2 – tall (15 m) trees	1/1/2007-31/12/2011	1/1/1993 – 31/12/2006

Table 6

Vegetation parameters used in the Shetran simulations of Coalburn. The canopy drainage parameter C_k is the rate of drainage when the canopy is at its storage capacity and C_b is used in an exponential function to describe how the drainage rate falls as the canopy dries (Rutter et al., 1972). Canopy resistance is the value at field capacity: in the model it increases with soil moisture tension. A range of values is given for the canopy storage and the leaf area index, characterized by a seasonal variation with lower values in the winter and higher values in the summer. ¹ parameter was calibrated. ² the actual aerodynamic resistance varies with the wind speed, the value here is calculated using the average wind speed of 2.8 m/s.

Parameter	Scenario 1:	Scenario 2:	Grass
	Small (8 m) trees	Tall (15 m) trees	
Canopy Drainage - C_k (mm/s)	1.9E-5	1.9E-5	1.9E-5
Canopy Drainage - C_b (mm^{-1})	3.2	3.2	3.2
Canopy Storage (mm)	0.5 – 1.0 ¹	1.5 - 3.0 ¹	0.1 - 0.8 ¹
Rooting Depth (m)	1.2	1.2	1.2
Aerodynamic Resistance (s/m)	20.4 ²	15.0 ²	53.6 ²
Leaf Area Index (-)	5.0 - 6.0	5.0 – 6.0	1.2-4.8
Canopy Resistance (s/m)	120 ¹	120 ¹	120 ¹

Table 7

Soil Parameters used in the Shetran simulations of Coalburn. ¹parameter was calibrated (see text for details)

Parameter	Value
K_{sat} (m/day) 0 – 0.1 m below ground	20 ¹
K_{sat} (m/day) 0.1 m– 0.4 m below ground	2.0 ¹
K_{sat} (m/day) 0.4 m – 0.7 m below ground	0.2 ¹
K_{sat} (m/day) 0.7 m – 1.2 m below ground	0.02 ¹
Saturated water content (-)	0.80
Residual moisture content (-)	0.30
Van Genuchten alpha (m^{-1}) 0 – 0.4 m below ground	2.0
Van Genuchten alpha (m^{-1}) 0.4 m – 1.2 m below ground	0.5
Van Genuchten n (-)	1.2

Table 8

Shetran simulation results from the two scenarios for five-year periods. Ratio is the measured discharge / simulated discharge and NSE is the Nash-Sutcliffe efficiency.

	Scenario 1 (small trees)				Scenario 2 (tall trees)		
	Mean Measured discharge (m ³ /s)	Mean Simulated discharge (m ³ /s)	Ratio	NSE	Mean Simulated discharge (m ³ /s)	Ratio	NSE
1993-1996	0.039	0.038	1.04	0.91	0.031	1.27	0.86
1997-2001	0.044	0.047	0.93	0.89	0.040	1.11	0.90
2002-2006	0.039	0.043	0.91	0.89	0.036	1.09	0.90
2007-2011	0.043	0.052	0.83	0.82	0.044	0.97	0.91

Figures

Fig. 1 a) Map showing the Coalburn catchment boundary (© Crown Copyright/database right 2014. An Ordnance Survey/EDINA supplied service), b) Aerial photograph (copyright Google, Infoterra Ltd and Bluesky), c) Shetran mesh and stream channels (50-m grid squares).



Fig. 2 Comparison of annual precipitation and annual streamflow totals (mm) at Coalburn. The black diamonds show the values before ploughing, after ploughing there is an initial increase in discharge and then a decrease as the forest grows. The dashed line shows the change, with all the points, except one, from 1967-1996 above the line and all the points from 1997 - 2011 below the line.

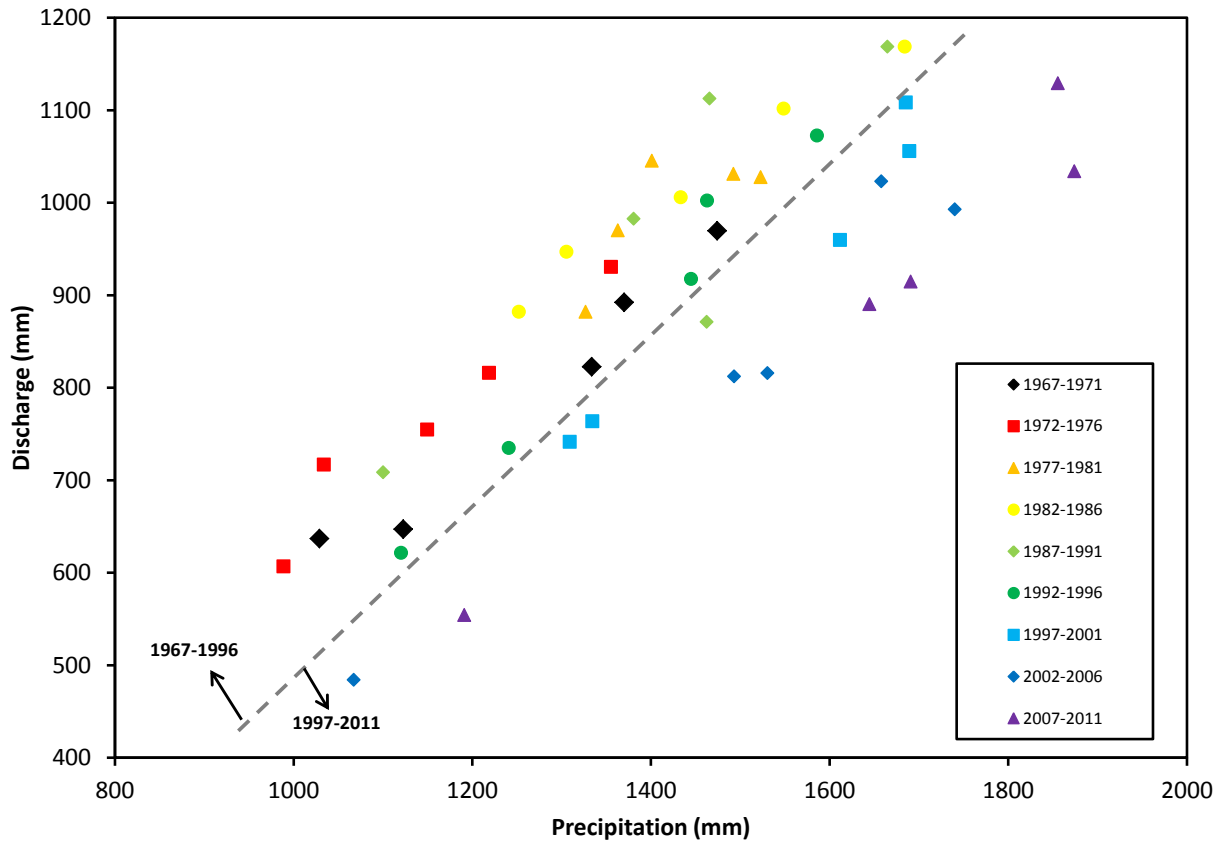


Fig. 3 Cumulative water losses(mm) at Colaburn between 1972 and 2001 for the reference crop potential evapotranspiration, the actual evapotranspiration and the difference between the two.

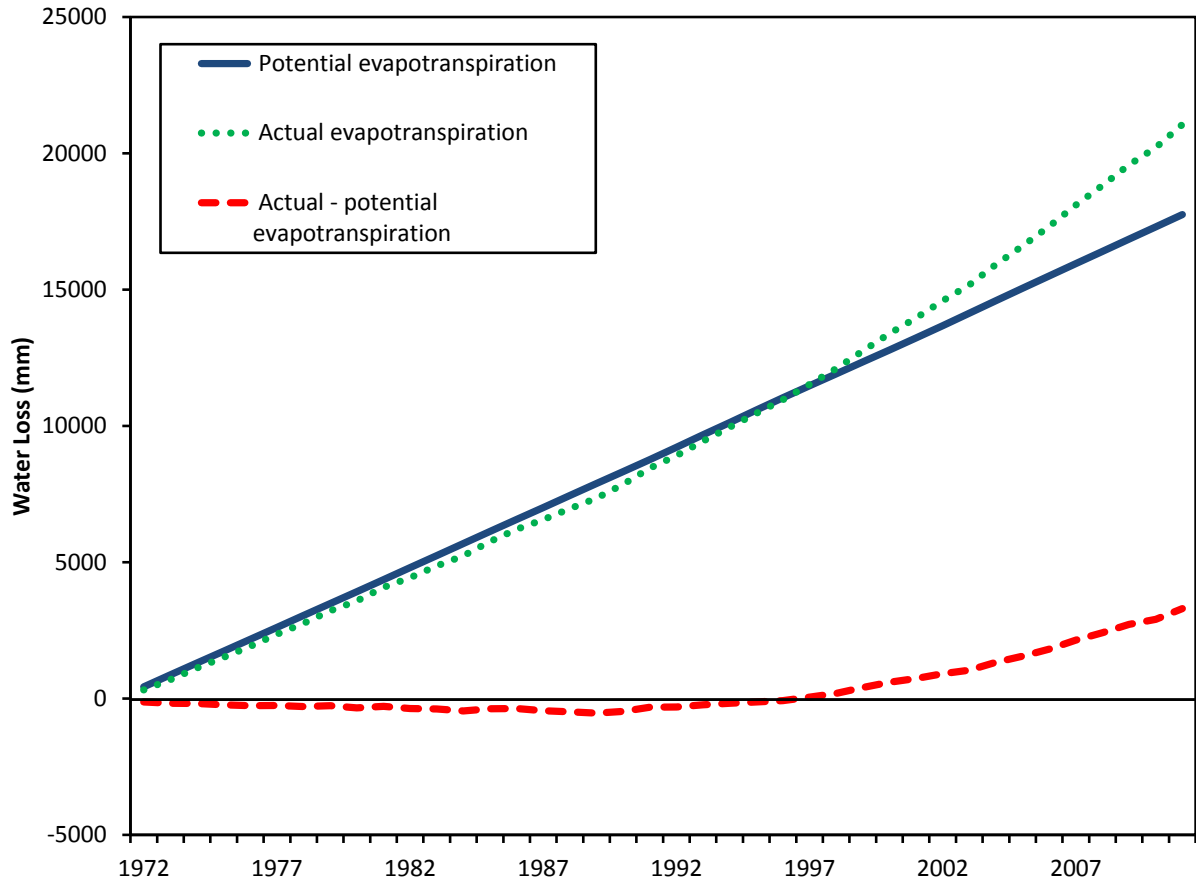


Fig. 4 a) Annual precipitation totals, b) annual discharge totals, c) annual maximum discharge and d) number of individual peaks over a threshold discharge of 2 mm/hr. Owing to major gaps in the discharge records the peaks from 1972, 1973, 1990 and 1991 have been removed. The data for 1967-71 are before the ploughing and for 1974-2011 after the ploughing.

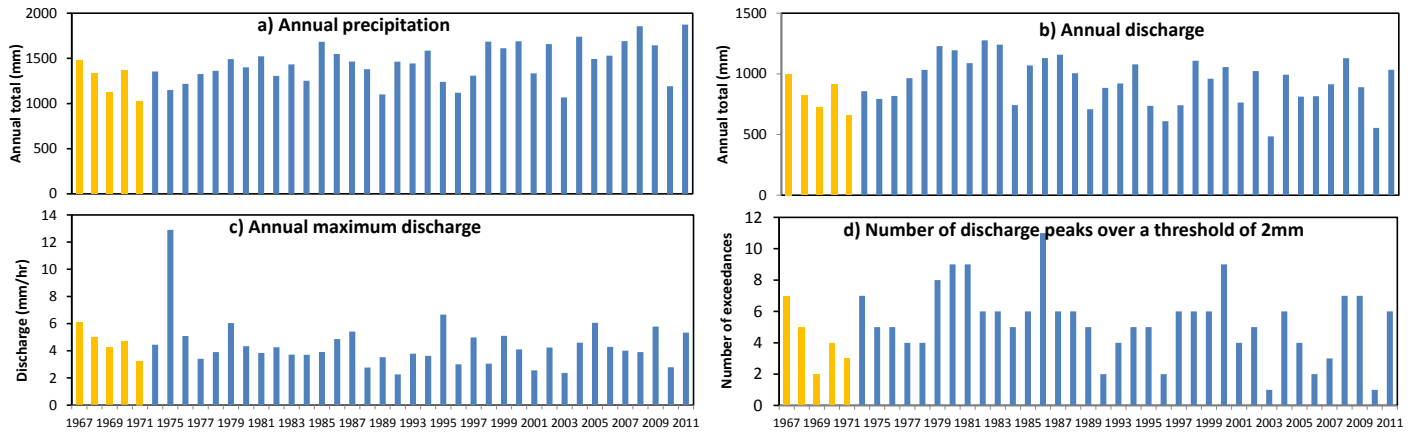


Fig. 5 Flow duration curves for the Coalburn catchment 1967-2011. The thicker black line shows the curve before ploughing.

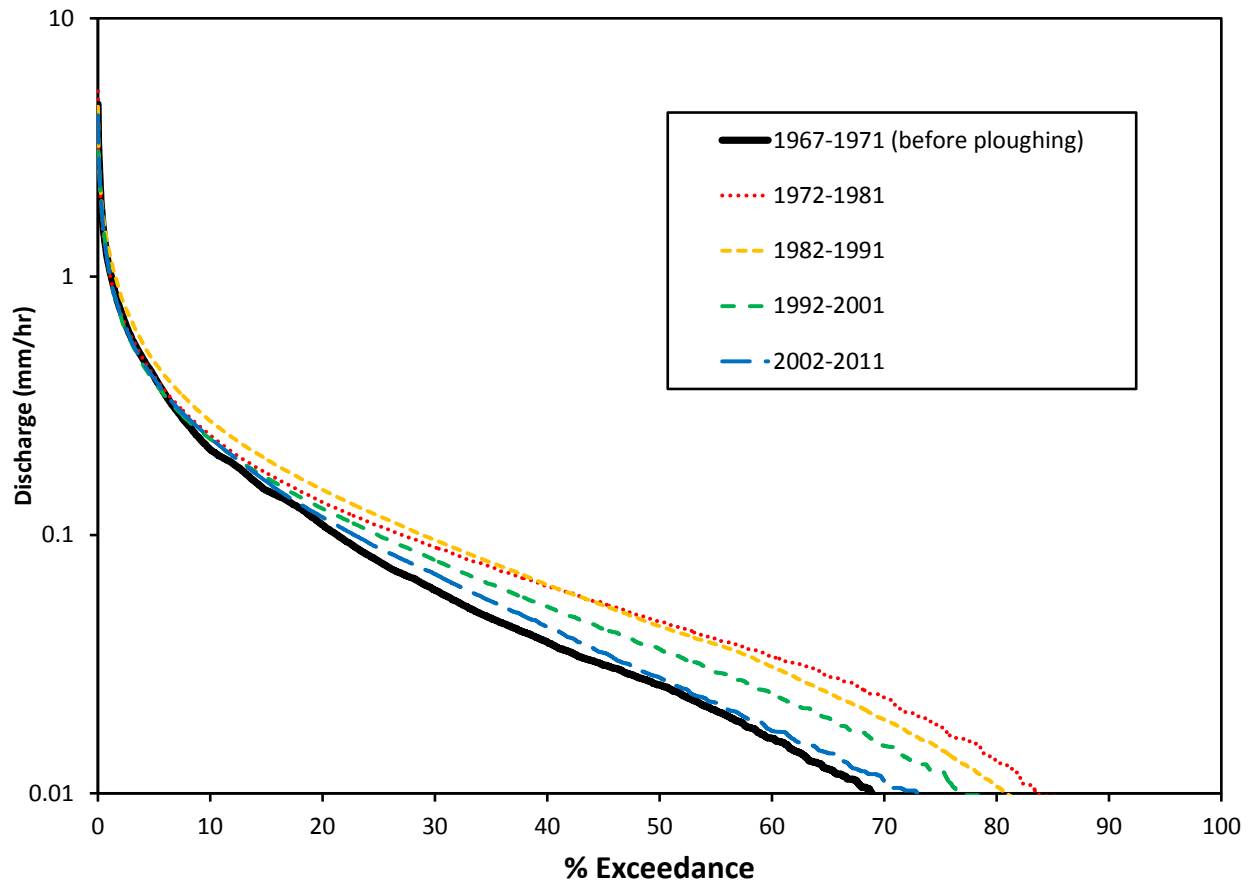


Fig. 6 Annual base flow index for the Coalburn catchment 1967-2011. The diamonds show the value before ploughing and the squares after ploughing. Owing to major gaps in the discharge records the peaks from 1972, 1973, 1990 and 1991 have been removed.

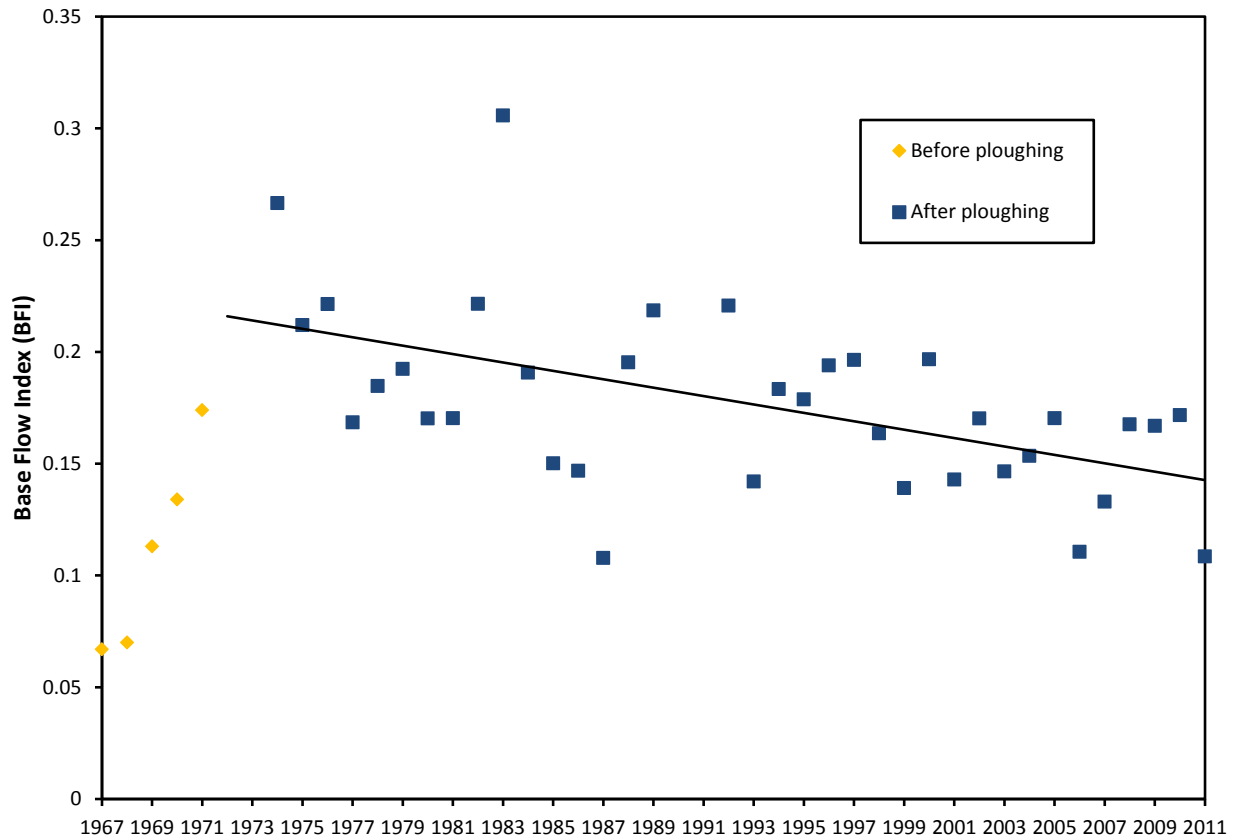


Fig. 7 Recessions in the Coalburn catchment, showing the change in discharge (\dot{Q}) for a particular discharge (Q). The thicker black line shows the curve before ploughing.

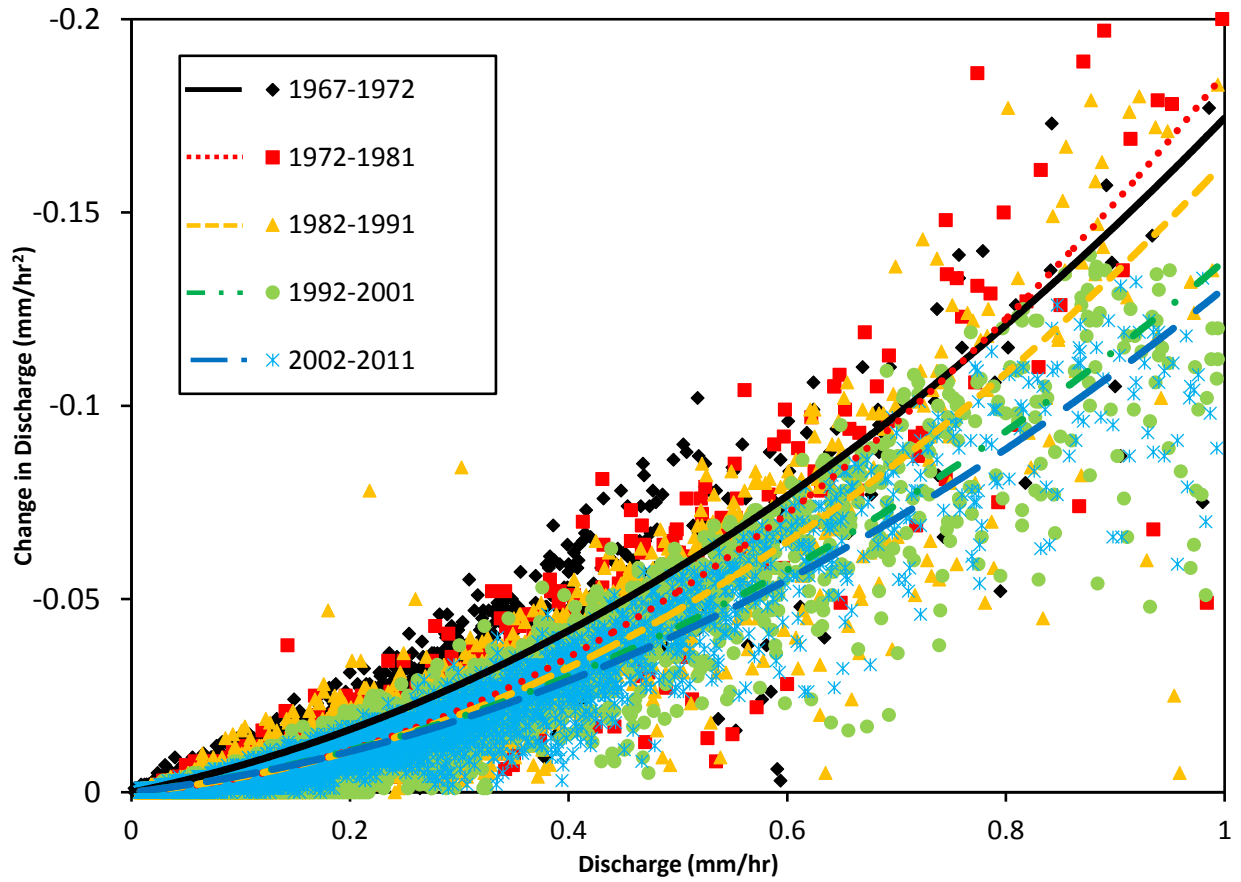


Fig. 8 Maximum daily measured and simulated discharges in the Coalburn catchment for both scenarios 1 and 2 in a) 1993-1996 and b) 2007-2011.

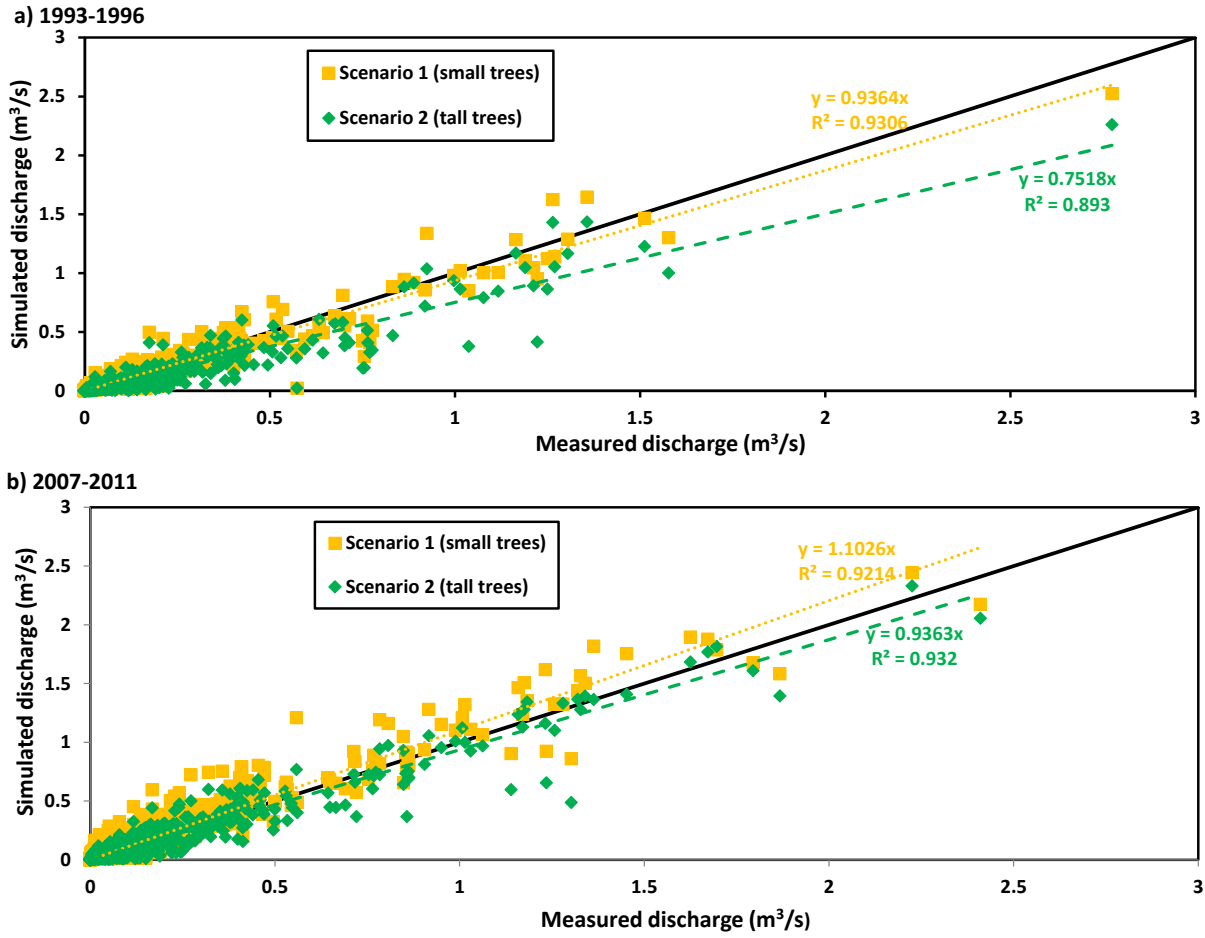


Fig. 9 Measured and simulated discharges in the Coalburn catchment for both scenarios 1 and 2 for the large event in January 2005.

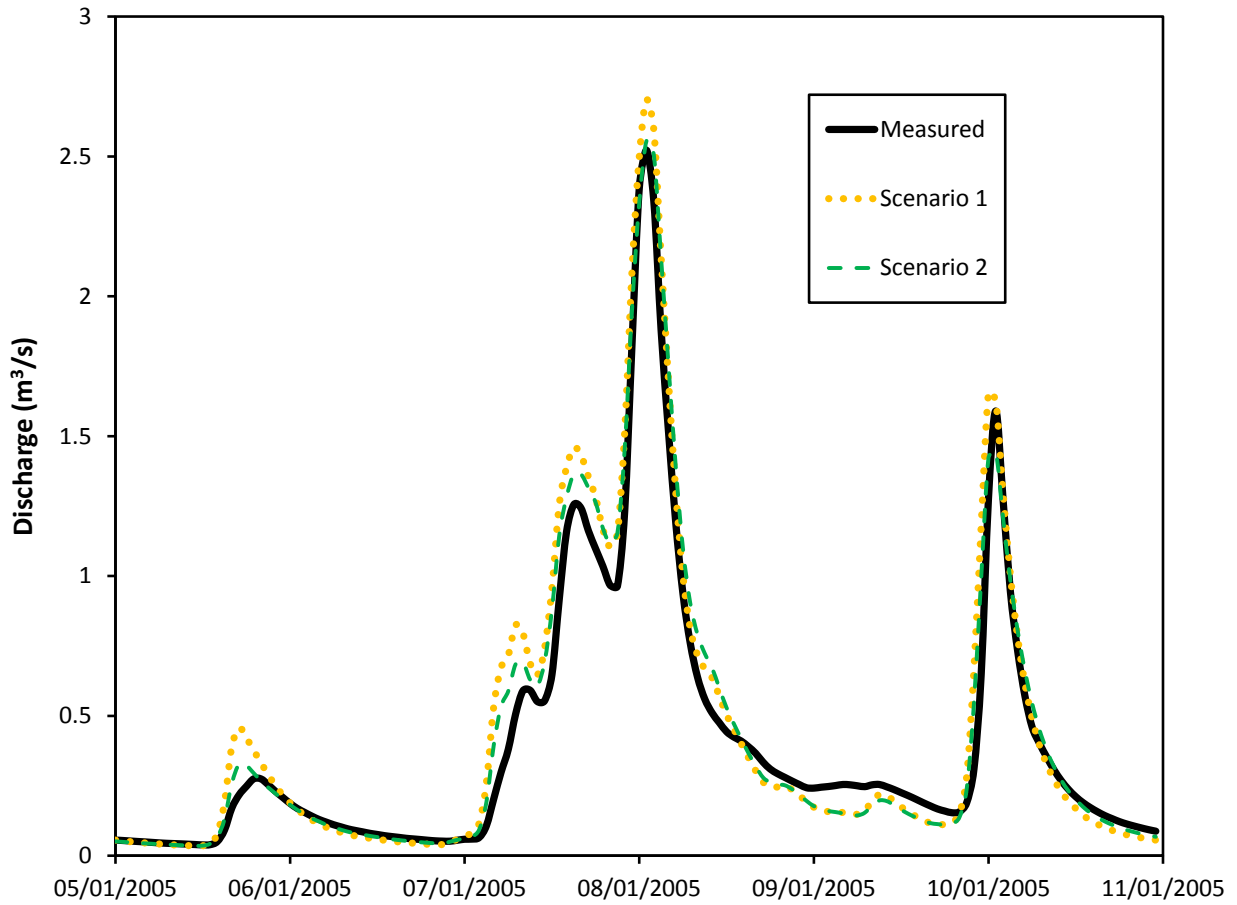


Fig. 10 Annual measured and simulated discharges in the Coalburn catchment for 1993-2011. a) Mean annual discharge, b) Ratio of measured/simulated discharge.

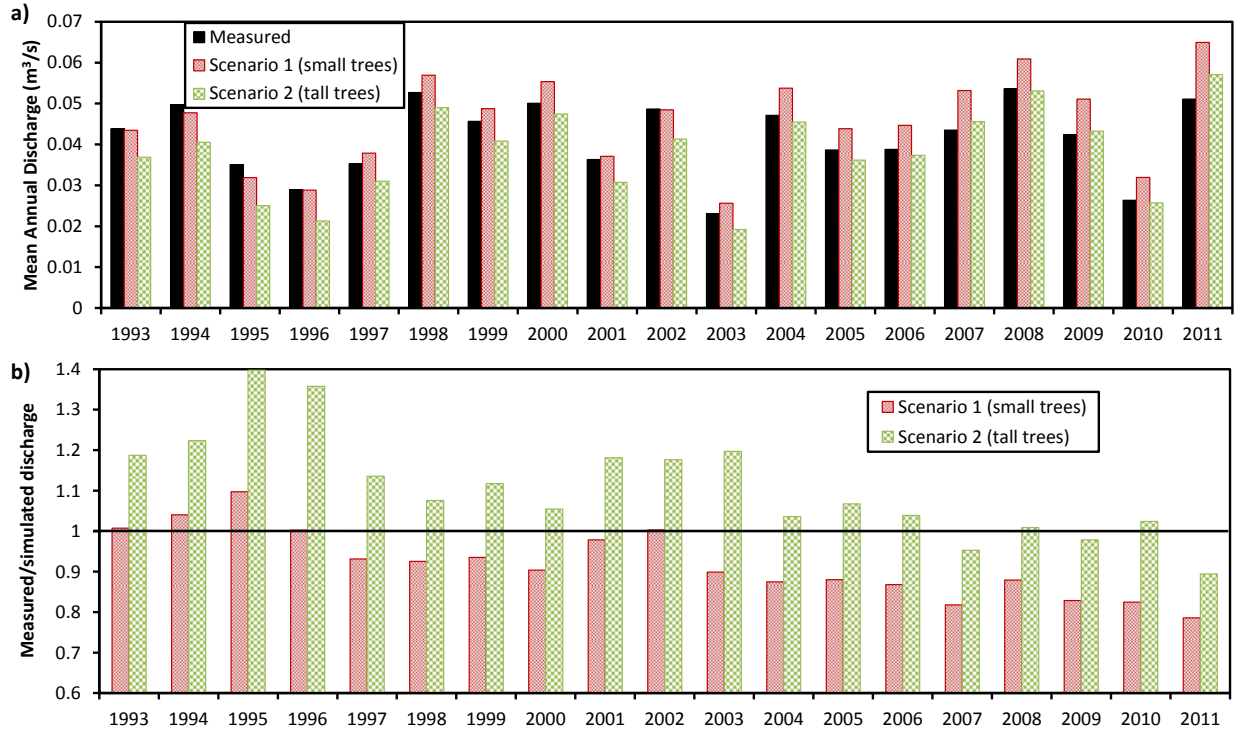


Fig. 11 Comparison of maximum daily discharge (m^3/s) for scenario 1 and scenario 2 from the 19-year Shetran simulation of the Coalburn catchment. The line of equality is shown.

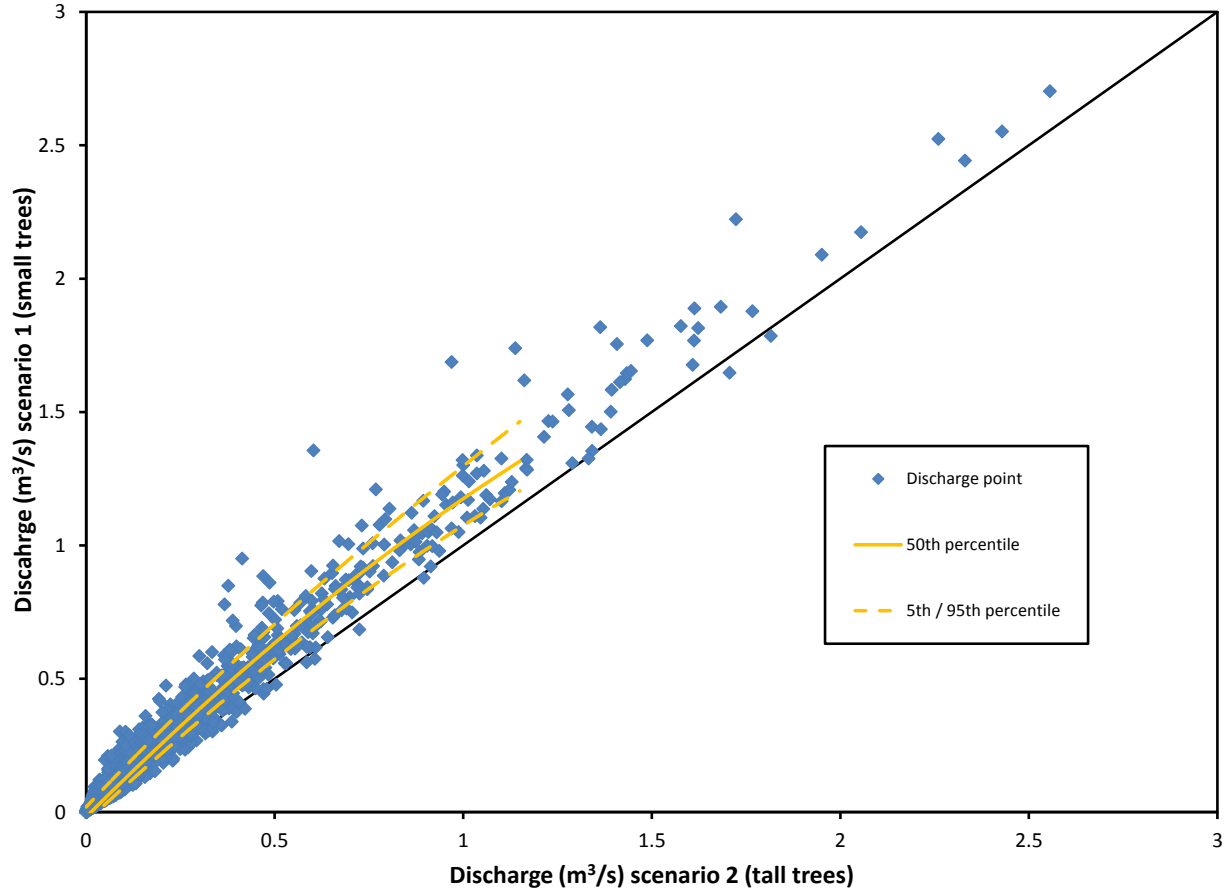


Fig. 12 Gumbel plot of annual maximum discharge (m^3/s) for the two scenarios from the 19-year Shetran simulations (1993-2011) of the Coalburn catchment. The change in frequency between scenario 1 and 2 for three return periods is shown.

