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Identifying step changes in single streamflow and evaporation records due to forest cover change

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Abstract:

Techniques that identify forestry-induced changes to streamflow or evaporation are needed to assess available water resources. Equally, there is a growing appreciation that climate cycles may be having a profound impact on the land-surface hydrology. The ability to see forestry-induced change above the effects of climate dynamics, therefore, becomes a critical issue. Paired-catchment analyses have proved very valuable in identifying change, but cannot quantify the relative impacts of climate and land-cover change, and data from adjacent reference basins are not always available. Within this study, we examined whether step changes within single time-series of streamflow or evaporation (P-Q) could be identified without reference to those of a control catchment. The UC-DHR method was used for this analysis, and included a special routine to allow a known change-point (e.g. start of logging) to be specified or alternatively identified by the model. Data from three experimental catchments important for their seminal forestry impact studies were selected for the analyses.

The study demonstrated that clear-cutting 29% of the Hore catchment and 40% selective felling of the Berembun basin produced a step change in the discharge trend that was clearly observable above the climate-related dynamics and uncertainty. In contrast, step changes in P-Q following the same selective felling event or following 22% afforestation of the Upper Hodder basin were not larger than the uncertainty bands or magnitude of the inter-annual cycles produced by the climate dynamics, respectively. This demonstrates that while step changes can be observed in single hydrological time-series, errors within the observations can sometimes mask the identification of change. This masking of change is also possible where the longer-term cyclical behaviour in Q or P-Q from natural climate dynamics is large, while the spatial extent of forestry change is small. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS afforestation; logging; Plynlimon; unobserved components—Dynamic Harmonic Regression; Tropics

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INTRODUCTION

Identification of the *observed* effects of forest cover change on the components of the hydrological cycle is an issue of current concern for those seeking to maximize water yield (Law, 1956; Calder and Newson, 1979; Wilk and Hughes, 1992; Wang *et al*., 2008), mitigate flooding (Jones and Grant, 1996; Robinson *et al*., 2003), quantify catchment nutrient budgets (Bormann *et al*., 1997), mitigate forestry impacts (Thang and Chappell, 2004) and provide observations to evaluate the simulations of land surface schemes within global climate models (e.g. Chahine, 1992; Polcher, 1995; Rajendran *et al*., 2002; Roy and Avissar, 2002; Eckhart *et al*., 2003; Ma *et al*., 2010).

The most fundamental unit for the study of the components of the hydrological cycle is the catchment and its components are often described via a catchment water budget (Gregory and Walling, 1973). Over the long term, the precipitation (P) received by a land area is equal to the stream discharge draining through a gauging station (Q) less losses by total evaporation (E) and deep percolation (G) that do not return to the stream upstream above the point of where Q is measured. Inter-annual variations in subsurface water storage (ΔS) become important where catchments overlie extensive and deep aquifers (Todd, 1980). In the case of catchments that are not underlain by aquifers, this change in storage only becomes an important component over periods of less than one year (Lee, 1970; Gregory and Walling, 1973; Hudson *et al*., 1997). Thus, for a catchment on a non-aquiferous geology, the water budget formula for annual integration periods would be:

$$P_i = Q_i - E_i \pm G_i; \tag{1}$$

Where i is the year, P_i is the annual preciptation (mm/yr), Q_i is the annual stream discharge (or streamflow) measured at a specified gauging station (mm/yr), E is the actual, annual evaporation, including the components of wet-canopy evaporation (or interception loss), transpiration, and soil evaporation (mm/yr), and G_i is the annual subsurface percolation that does not leave the catchment by evaporation or flow through the specified stream gauging station (mm/yr). Term G_i, or the subsurface waters not returning to the stream channel prior to the stream gauging station (i.e. exiting the catchment via the subsurface) needs to be quantified at annual time-steps for catchments on aquifers or on non-aquifers when surface-defined catchment areas are very small, i.e.

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less than 10 hectares (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Chappell *et al*., 1999). For larger catchments (>10 ha) the annual G_i term for non-aquiferous catchments reduces to zero. In such circumstances, an estimate of the catchment-wide, annual evaporation (E_i) becomes:

$$E_i = P_i - Q_i \tag{2}$$

Indeed, at the 1–10 km^2 scales of many research catchments (Bosch and Hewlett, 1982; Calder, 1986; Bruijnzeel, 1990), the micro-meteorological estimates of evaporation sometimes can be less accurately determined in comparison to estimates of catchment precipitation minus stream discharge, $P_i - Q_i$ (Morton, 1985; Hudson *et al*., 1997; Wilson *et al*., 2001; Ford *et al*., 2007; Marc and Robinson, 2007).

As forest vegetation tends to evaporate different (often greater) quantities of water than lower vegetation at adjacent locations (Bosch and Hewlett, 1982; Calder, 1986; Bruijnzeel, 1990, 2004), extensive changes in forest cover are likely to result in observable changes to the catchment-wide, evaporation (E_i). Greater losses of E_i would leave less subsurface water available for the generation of streamflow, thus annual streamflow (Q_i) would increase. Use of the catchment water budget, therefore, allows landscape-scale changes in both E_i and Q_i as a result of forestry operations, to be examined.

Identification of forestry effects on water budgets

A wealth of findings related to the hydrological impacts of forestry management have been gained by the use of 'paired catchment studies' where hydrological flows from an undisturbed catchment are compared with those from a nearby catchment differing only in the nature of the forestry disturbance (e.g. Bates and Henry, 1928; Hibbert, 1967; Hewlett *et al*., 1969; Patric and Reinhart, 1971; Harr and McCorison, 1979; Bosch and Hewlett, 1982; Swank *et al*., 1988; Bruijnzeel, 1990, 2004; Kirby *et al*., 1991; Malmer, 1992; Watson *et al*., 1999, 2001a; Wei *et al*., 2008). Most of these studies have been undertaken at the relatively small scale of a 1–10 km^2 experimental catchment (*op. cit.*). Increasingly, forest managers, water supply engineers, governmental policy makers, and climate modellers are requesting information on the nature of hydrological impacts resulting from land cover changes undertaken over much larger spatial scales (Newson and Calder, 1989; Bonell, 1999; NRC, 2008). Over these larger scales it is much more difficult to undertake paired catchment studies, as it is difficult to find two catchments with similar ground and climatic characteristics to compare their differences in forestry or indeed other forms of land management. Estimation of hydrological changes at these larger scales has been addressed with physics-based models (e.g. Lukey *et al*., 2000), but there are increasing concerns (Beven, 2001; Eckhardt *et al*., 2003; O'Connell *et al*., 2007) over the representation of subsurface hydrological parameters at catchment scales and in the uncertainties produced by models which have a high demand for distributed input parameters (e.g. Anderton *et al*., 2002). Added to this, is an increasing perception that the cycles and shifts in the climate may be affecting the absolute and relative magnitude of hydrological changes resulting from forest change (Bonell, 1998). While the paired catchment approach shows those changes additional to the natural dynamics observed within a control catchment, it does not quantify the amplitude of the natural dynamics for comparison with the amplitude of the land-use related effects. If the streamflow and evaporation show climate-related dynamics, then the amplitude of the change resulting from land-use change may be different if it takes place at a different point on climate cycles, such as those related to monsoons or the El Niño-Southern Oscillation (e.g. Kiem and Franks, 2001). This becomes particularly important where hydrological flows are non-linearly related to the climate forcing, as is the case of rainfall-runoff behaviour or sediment delivery in humid catchments (e.g. Chappell *et al*., 1999, 2004).

Techniques that do not require paired catchment analysis, but can identify changes within a single series of streamflow (Q) or evaporation (from longer-term P-Q), are needed for applications where adjacent reference catchment data are not available (Shuttleworth, 1988). Further, techniques that can separate the role of largely natural (climate-related) dynamics relative to the land-use change effects would give more robust interpretations of change (Schulze, 2000). Clearly, if identified changes are to be accepted, the uncertainties in the analyses must be presented also (Eckhardt *et al*., 2003). Several Data-Based-Mechanistic (DBM) modelling methods have the potential to identify both climate-related and land-use-related impacts on a single time series of Q or E, together with associated model uncertainty.

Introduction to the DBM modelling tools

The DBM tools are a suite of dynamic and non-linear models for the analysis of time-series data (Young, 1998, 2001). Within all, the modelling begins by minimising the assumptions about the nature of the data distributions or structure of physical (e.g. hydrological) system. A range of models is then identified, together with a series of the objective statistical criteria by which the model performance is judged. Lastly, those model structures that are statistically acceptable are then further assessed by their consistency with the perceived nature of the physical system (Young, 2001). Uncertainty information is produced by all the tools that form the DBM suite. Tools that have been developed under the DBM methodology include: the Dynamic Transfer Function (DTF) model, Dynamic Auto-Regression (DAR) model, Dynamic Linear Regression Model (DLR) model, and of relevance to this work the Unobserved Components—Dynamic Harmonic Regression (UC-DHR) model (Young, 2001; Tych and Chappell, 2003).

Longer-term (monthly, yearly or inter-annual) cycles in the climate can be seen within streamflow data and may include the effects of the Madden-Julian Oscillation, MJO (Madden and Julian, 1971, 1972, 1994), monsoon cycle (Archer and Fowler, 2004), Indian Ocean Dipole (IOD) (Saji *et al*., 1999), El Niño Southern Oscillation, ENSO (Foley *et al*., 2002; Franks and Kuczera, 2002) and North Atlantic Oscillation (NAO) (Trigo *et al*., 2004). The specific DBM tool known as the UC-DHR model of Young *et al*. (1999) has been used by Chappell *et al*. (2001, 2004) to identify some of these climatic cycles.

Where the timing of the onset of a land-use change, such as deforestation or afforestation is known, this might be incorporated within UC-DHR analysis by allowing a much larger parameter variance at the start of the period of known land-use change. This can be achieved using the Variance Intervention routine of Young and Ng (1989) and Ng and Young (1990). If the step-change in the longer-term trend of the modelled of Q or P-Q time-series is larger than the uncertainty bands on that component of the trend associated with climate-related dynamics, then a land-use-related impact could be said to be identifiable.

Aim and tasks

Within this paper, the impacts of land-use change are separated from the natural climate dynamics using UC-DHR analyses. Specifically, the presence of step changes in streamflow and/or evaporation (P-Q) time-series larger than the effects of natural climate dynamics are quantified using the analyses. To achieve this aim the specific details of the UC-DHR model and the associated Variance Intervention routine are first described. The hydrological data from a seminal study undertaken within the humid tropics, where Q and P-Q changes have been shown to occur by paired catchment analysis are examined next. The model is then applied to seminal forest hydrology studies from humid temperate UK, but where appropriate paired catchment analyses were not available.

CATCHMENT DATASETS

The investigated humid tropical study with published paired catchment analysis had been undertaken for a site within Peninsular Malaysia, while those example studies lacking full paired catchment analyses (for the specific basins studied here) were for humid temperate sites on Bowland Fells (NW England, UK) and Plynlimon massif (mid-Wales, UK). These three datasets were chosen for reanalysis because they represent seminal studies for scientific research on the forestry impacts on hydrology within the humid tropics and humid temperate UK.

Bukit Berembun selective logging study

The paired catchment study was undertaken within the Bukit Berembun Forest Reserve, Negri Sembilan State, Peninsular Malaysia. Monitoring of three catchments covered by natural rain forest began in 1981 (Figure 1(a)). Two of the catchments were disturbed by 'selective logging' over several months following its initiation in July 1983. Some 40% of the standing timber stock was extracted from the 13·3 ha C1 catchment by conventional harvesting methods, while 33% of the timber was extracted from the 30·8 ha C3 catchment by Reduced Impact Logging (or 'supervised logging': Chappell *et al*., 2004) methods. As the canopy of uncut trees was damaged during the harvesting process, the extent of intact canopy may be smaller than that indicated by the extraction volumes. A further catchment, the 4·6 ha C2 catchment was left as a control catchment. Reliable streamflow data from the three 120° V-notch weirs continued to be monitored until the end of 1989. All three catchments were located on a weathered granite geology (Abdul Rahim, 1990; Chappell *et al*., 2004). A double mass curve (after Searcy and Hardison, 1960) of streamflows from the disturbed catchments against those from the control catchment presented in Abdul Rahim and Harding (1992) indicated a change following logging in July 1983 (C3 is not discussed further).

For our identification of forest cutting impacts on the time-series of streamflow (Q) and evaporation (P-Q) we

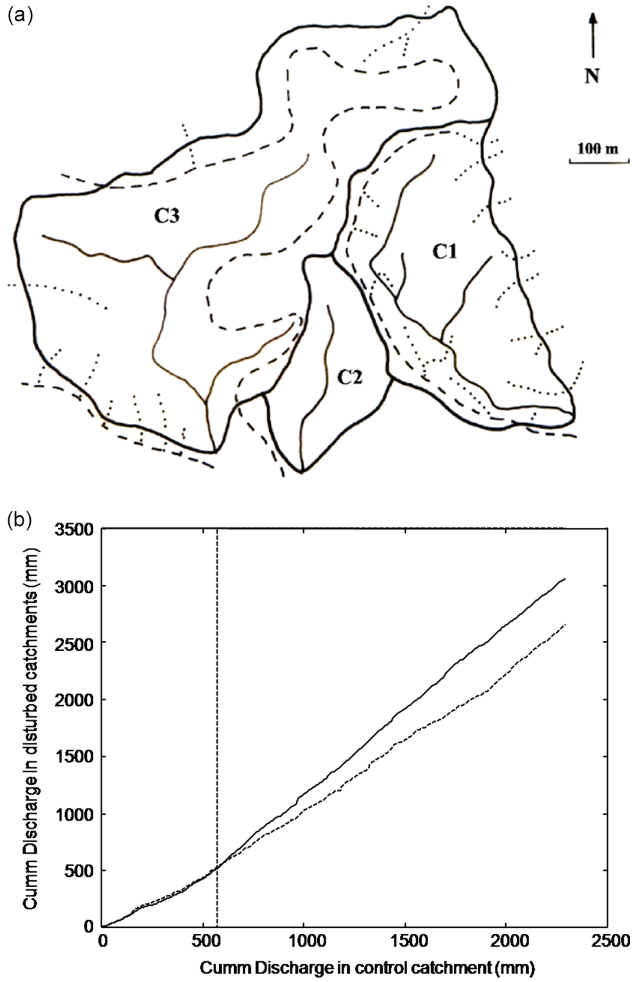

Figure 1. The Bukit Berembun experimental study at 2°46′N, 102°6′E in Negri Sembilan state, Peninsular Malaysia: (a) a map of the Bukit Berembun C1, C2, and C3 catchments, where the catchment divides are shown with a broad solid line, streams with a fine solid line, roads with a dashed line and skid trails with a dotted line, and (b) the double mass curve of streamflow for the conventionally-logged (C1) catchment against that of the control (C2) shown with a solid line and the 1 : 1 relationship with a broken line

used monthly data for the period 1981–1987 digitized from those published in Abdul Rahim and Harding (1992). Data for the conventionally logged C1 catchment were used and compared with the cycles within the local precipitation, and its effects propagating to the streamflow records of the undisturbed C2 catchment. The inter-annual cycles in the rainfall were also examined from the longer-term (102-year: 1891–1992) records from the Jelebu rainguage (2°57′N, 102°4′E) 30 km to the north of the experimental catchments. These data were provided by Leong Chow Peng (Malaysian Meteorological Department).

Upper Hodder afforestation study

In 1955, water engineer Mr Frank Law established a 450 m^2 lysimeter containing Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees planted in 1923. This lysimeter is within a small stand of trees on the edge of the catchment of the 12000 Ml Stocks reservoir (NW England, UK; Figure 2(a)). It was established by Law because of his awareness of the literature (Santing, 1953; Ovington, 1954) which indicated a greater loss of water resources to evaporation by planted conifers than the upland grassland that they replaced (Law, 1956, 1957). Early results from this study indicated that the monetary value of the water resources lost to evaporation and hence not entering the reservoir of the then Fylde Water Board (now part of United Utilities, plc) was greater than the revenue paid to the water board by the Forestry Commission for their right to grow trees within the catchment owned by the water board (Law, 1956). These results were controversial and seen as atypical by some, for example, Penman (1963). The work did, however, stimulate debate and led to the establishment of the paired Wye and Severn headwater catchments on the Plynlimon massif (mid-Wales) by the Hydrological Research Unit, which became the UK Institute of Hydrology (Kirby *et al.*, 1991), and more recently, Centre for Ecology and Hydrology (CEH). These catchments were gauged specifically to address the question of whether planted conifers have a greater evaporation than the upland grassland that they replaced. The 30 years of water balance studies at Plynlimon, with various improvements in the measurements and calculations, did indeed show that conifers can lose more water to evaporation in comparison to nearby upland grasslands (Institute of Hydrology, 1976; Hudson and Gilman, 1993; Hudson *et al.*, 1997). Plot-scale studies within the Severn catchment have also shown that it is the very high rates of wet-canopy evaporation (or 'interception loss') in areas of low intensity, long duration rainfall and relatively windy conditions that account for the large losses by planted conifers (Calder, 1990; Kirby *et al.*, 1991).

Paralleling Law's water budget measurements on his lysimeter, Law also calculated the water budget for the whole contributory area of Stocks reservoir, the 37·5 km^2 Upper Hodder catchment (Figure 2(a)) for the period 1956–1965 inclusive (Law, 1956, 1957, 1964; Fylde Water Board, 1966). The precipitation component

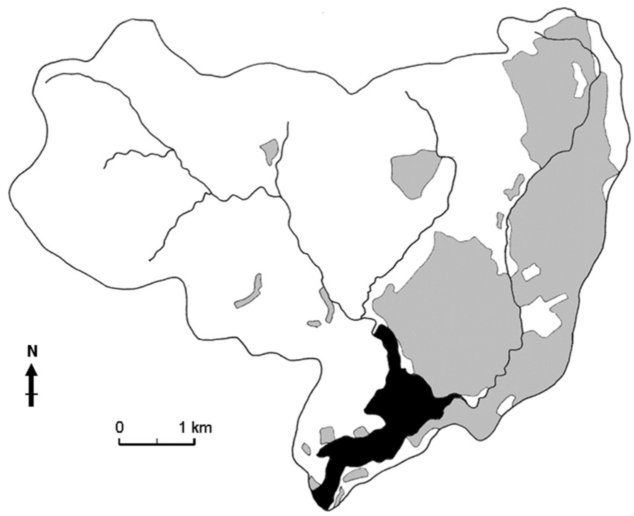

Figure 2. Map of the Upper Hodder catchment at 54·0 °N, 2·6 °W in northwest England, UK. The broken line shows the boundary of the Upper Hodder catchment, the half-tone shading the maximum extent of Gisburn Forest within the catchment, the solid line the stream channels, and solid shading the extent of Stocks reservoir

was derived from 22 raingauges distributed across the catchment, while the stream inflows to the reservoir were estimated by a monthly summation of the reservoir overflow, change in reservoir storage, compensation release and water supply abstraction. Walsh (1977) later extended the stream inflow component of the monthly water budget calculation to cover the longer period of 1927–1976.

The principal phase of conifer planting within the Upper Hodder catchment began in 1953, following the leasing of some 22% of the catchment to the Forestry Commission in 1947 (Calder *et al.*, 1982; Figure 2(a)). From the Gisburn Forest Management Inventory for the 10·6 km^2 Bottoms Beck tributary of the Upper Hodder (1978–1999) felling of 2·71 km^2 of these planted conifers took place in the 1980s and 1990s (forest inventory map: Forest Enterprise, personal communication).

As part of a larger study estimating the drought inflows into the reservoir, Walsh (1977) had examined the time series of stream inflow and noted declining inflows over the period 1954–1969, which he tentatively attributed to the effects of the afforestation. Within this study, we aim to identify if a step change in the evaporation (P-Q) can be seen above the natural cycles resulting from the rainfall signal. The monthly discharge (Q) for the period 1928–1986, and precipitation (P) from 'Stocks gauge 10' (1928–1935) and nearby 'Stocks gauge 11' (1936–1986) were obtained from United Utilities, plc, and the British Atmospheric Data Centre (BADC), respectively.

Afon Hore deforestation study

The two experimental catchments established on the Plynlimon massif following the seminal work by Frank Law in the Upper Hodder catchment are both approximately 10 km^2 in area. At the start of our study period, the Severn experimental catchment was 66% afforested with conifers, while the Wye experimental catchment was a mix of improved grassland and rough pasture. Reliable streamflow records have been available from both catchments since 1975 (Kirby *et al*., 1991).

The blocks of conifers within the Severn catchment form part of the Hafren Forest, which is managed by the Forestry Commission. Most of this forest was planted since 1937/1938 (Newson, 1976) and as a consequence of the 50-year felling cycle, extensive felling began in the mid-1980s.

Both catchments include a series of nested contributory catchments, with the 8·7 km^2 Severn catchment including the 3·67 km^2 Hafren, the 0·89 km^2 Nant Tanllwyth, 3·08 km^2 Afon Hore and its headwater tributary the 1·6 km^2 Upper Hore. Over the period December 1985 to October 1987, some 29% (90·8 ha) of the 3·08 km^2 Afon Hore catchment was clearfelled (Roberts and Crane, 1997; Robinson and Dupeyrat, 2005). All this extraction was in the lower reaches of the Afon Hore catchment (Figure 3(a)). Monitoring had been initiated at the Afon Hore gauging structure in 1973 and continues to date. As monitoring of the Upper Hore only began just prior to the start of logging in the lower reaches of the Afon Hore, a cutting-related inflection in a double mass curve (after Searcy and Hardison, 1960) cannot be plotted for this catchment pair.

For our identification of deforestation (i.e. clearance) impacts on the time-series of streamflow (Q) and evaporation (P-Q) in the Afon Hore we used daily data from 1975 to 1997 (Figure 3(b)) that we subsequently integrated over two-week periods. The local precipitation data were monitored at the Moel Cynnedd raingauge, less than 250 m to the north of the catchment (Figure 3(a)). All raw data were obtained from Frank M Law junior (formerly CEH).

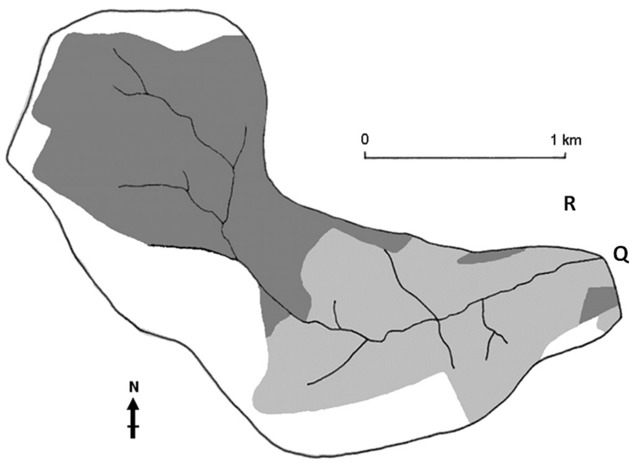

Figure 3. Map of the Afon Hore catchment showing the clear-felled forest coupes within the lower reaches (modified from Roberts and Crane, 1997) that is located within the 8·7 km^2 Severn experimental catchment on the Plynlimon massif, mid-Wales, UK (52·4 °N, 3·7 °W). The solid line shows the boundary of the Afon Hore catchment and the stream channel. The dark shading shows the extent of forest inside the Afon Hore catchment, while the light shading shows the area of clearfelling between December 1985 and October 1987. Symbol Q shows the location of the Afon Hore flume and R the location of the Moel Cynnedd raingauge

UC-DHR TOOL

This is the first description of the UC-DHR model for a hydrological change application. The model of the fortnightly and monthly P, Q and P-Q observations is a combination of a trend model, a model of the shorter-term cyclical components and an error model that best capture the dynamics of a time series. These components are modelled by a set of stochastic state space equations, with covariance parameters (often termed 'hyper-parameters' to distinguish them from the explicit parameters of the UC model) estimated from the time series observations. These hyper-parameters define the nature of the model dynamics and the 'memory' in the associated adaptive estimation algorithm. Signal extraction is accomplished by a combination of a recursive Kalman Filter (KF) and Fixed Interval Smoothing (FIS) algorithms. These recursive algorithms have inherent adaptive capabilities and are capable of automatically handling missing data.

The UC-DHR model is part of the class of univariate UC models also including the Basic Structural Model and Dynamic Linear Model (Harvey, 1984; West *et al*., 1985). In detail, the UC-DHR model is characterized by a trend (T_t: inter-annual) component, a shorter-term periodic (C_t: cyclical annual and sub-annual) component and a zero mean observation error (e_t, with variance, σ_e^2) component, where the simulated time series of rainfall, streamflow or evaporation, y_t, is simply:

$$y_t = T_t + C_t + e_t \tag{3}$$

The most important of the components to be characterized in the present study is the shorter-term cyclical component:

$$C_t = \sum_{i=1}^{S_s} \{a_{i,t}\cos(\omega_i t) + b_{i,t}\sin(\omega_i t)\} \tag{4}$$

where $a_{i,t}$ and $b_{i,t}$ are stochastic Time Variable Parameters (TVPs) defining amplitudes of the harmonic sine and cosine components, and ω_i, $i = 1, 2, \ldots, S_s$ are the fundamental and harmonic frequencies associated with the periodicity in the series. In this study, the frequency values are chosen by reference to the spectral properties of the time series, as revealed by the standard Auto Regressive (AR) spectrum. In this application to P, Q and P-Q, they are most likely related to seasonality in the precipitation (e.g. Archer and Fowler, 2004). The trend component, T_t, which accounts for longer term (multi-year) changes in magnitude or level can also be considered as a stochastic, time variable (or intercept) parameter in the UC-DHR model.

The UC-DHR model can be considered as an extension of the classical, constant parameter Harmonic Regression (or Fourier series or trigonometric) model, in which the gain and phase of the harmonic components can vary as a result of temporal changes in parameters $a_{i,t}$ and $b_{i,t}$ of Equation (4). The $a_{i,t}$ and $b_{i,t}$ parameters, and trend component, T_t, are each defined by a two-dimensional, stochastic state vector $\boldsymbol{x}_{i,t} = \begin{bmatrix} l_{i,t} & d_{i,t} \end{bmatrix}^T$, where $l_{i,t}$ and $d_{i,t}$ are the changing level (or intercept) and slope, respectively, of the associated trend or Time Variable Parameters (TVPs). The stochastic evolution of each $\boldsymbol{x}_{i,t}$ vector is described by a Generalised Random Walk (GRW: Young *et al.*, 1999) process of the form:

$$\boldsymbol{x}_{i,t} = \mathbf{F}_i \boldsymbol{x}_{i,t-1} + \mathbf{G}_i \boldsymbol{\eta}_{i,t} \qquad i = 1, 2, \ldots, S \tag{5}$$

where $S = 1 + S_s$ and

$$\mathbf{F}_i = \begin{bmatrix} \alpha & \beta \\ 0 & \gamma \end{bmatrix}, \mathbf{G}_i = \begin{bmatrix} \delta & 0 \\ 0 & 1 \end{bmatrix} \tag{6}$$

This general model includes the Integrated Random Walk (IRW, where $\alpha = \beta = \gamma = 1$; $\delta = 0$), the scalar Random Walk (RW: scalar but equivalent to GRW, where $\alpha = \beta = \delta = 0$; $\gamma = 1$), the intermediate case of Smoothed Random Walk (SRW, where $0 < \alpha < 1$; $\beta = \gamma = 1$; and $\delta = 0$), and Harvey's Local Linear Trend (LLT, where $\alpha = \beta = \gamma = 1$; $\delta = 1$) and Damped Trend (DT, where $\alpha = \beta = \delta = 1$; $0 < \gamma < 1$; Harvey, 1989; Koopman *et al.*, 2000). Preliminary analysis of the data from the three case study basins quickly established that only RW and IRW models are necessary for satisfactory model identification (Table I) and subsequent forecasting performance.

The overall State-Space (SS) model is constructed by the aggregation of the sub-system matrices, as defined by the GRW models (Equation (5)). The resultant observation and state transition equations are then

$$\begin{aligned} &\text{Observation Equation:} \quad y_t = \mathbf{H}_t \boldsymbol{x}_t + e_t \qquad \text{(i)} \\ &\text{State Equations} \quad : \quad \boldsymbol{x}_t = \mathbf{F}\boldsymbol{x}_{t-1} + \mathbf{G}\eta_t \quad \text{(ii)} \end{aligned} \tag{7}$$

In this study, the trend in the rainfall, streamflow and evaporation (P-Q) is modelled as an IRW process and all of the TVPs in the periodic component are modelled as RW processes. In this situation, if $n = 2S$, then $\mathbf{F}$ is an *nxn* block diagonal with blocks defined by the $\mathbf{F}_i$ matrices in the GRW models; $\mathbf{G}$ is an *nxn* matrix constructed by the concatenation of the corresponding subsystem matrices $\mathbf{G}_i$ in GRW; $\mathbf{H}_t$ is an appropriately defined 1*xn* vector, which relates the scalar observation y_t to the state variables $\boldsymbol{x}_t$, so that it represents the UC-DHR model; and η_t is an n dimensional vector containing, in appropriate locations, the zero mean, white noise input vectors $\eta_{i,t}$ (system disturbances) to each of the GRW models. These white noise inputs are assumed to be independent of the observation noise e_t and have an assumed diagonal covariance matrix $\mathbf{R}$ (normally called $\mathbf{Q}$ in the time series literature, but in this article $\mathbf{R}$ is used to avoid confusion with streamflow).

Table I. Efficiency (Coefficient of determination, R^2) of the UC-DHR models fitted to the precipitation (P), streamflow (Q) and P-Q time-series (BB = Bukit Berembun)

Site	Variable	Model efficiency (R^2)	
		without variance intervention	with variance intervention
BB control (C2)	Q	0·969	0·973
BB control (C2)	P-Q	0·993	0·995
Jelebu	P	0·510	—
BB logged (C1)	Q	0·973	0·941
BB logged (C1)	P-Q	0·877	0·885
Afon Hore	P-Q	0·605	0·611
Moel Cynnedd	P	0·359	—
Upper Hodder	P-Q	0·552	0·556

Estimation of the time variable parameters

Estimation of the state variable parameters is achieved using a combination of KF and FIS, and is described in detail in Young *et al.* (1999). Here we identify only the main features of the procedures, which are critical for this work.

Firstly, the recursive character of this procedure allows for handling of missing values in the observation record. Both KF and the FIS recursions are implemented in a two-stage form, namely a prediction step calculating the predicted states (i.e. TVP values) based on the data so far, followed by the correction step (where observations are available).

Secondly, the covariance matrices of disturbances η_t and e_t, respectively, in the state and observation equations (Equation (7)), are estimated from the data in a simplified form, due to the univariate character of the observations. The algorithm uses not two matrices, but one, being the ratio of the matrix termed here $\mathbf{R}$—the covariance matrix of the state disturbance η_t and the variance σ of the observation disturbance, e_t. This ratio is called the Noise Variance Ratio (NVR) matrix and determines the volatility of the estimated states—TVPs of the Unobserved Components Model. The NVR matrix is usually treated as diagonal and its elements are estimated from the data using either fitting the pseudo-spectrum of the UC model or Maximum Likelihood estimation (Young *et al.*, 1999).

Finally, the KF-FIS estimation algorithm recursively produces both the vector of state estimates $\hat{\mathbf{x}}_t$ and their covariance matrix estimate $\hat{\mathbf{P}}_t$. The latter defines the *a priori* confidence in the subsequent state estimates and this property is utilized in the Variance Intervention technique.

Variance Intervention: a tool for detecting hydrological change

The Variance Intervention technique (Young and Ng, 1989) is made possible by the recursive character of the estimation algorithm. The principle is simple, namely a high level of uncertainty (i.e. large values in $\hat{\mathbf{P}}_t$ matrix in the estimation algorithm) is introduced at the time step where it is believed that the value of the estimated variable (such as trend) is changing. This is achieved by an instantaneous, controlled increase of the NVR values relevant to the changing component(s) of the series. The increase produces the effect of diffused priors (i.e. an effective re-initialisation of the estimation of selected components) at the intervention point, i.e. here, the start of forest change. The effect is such that the component (such as the level of the trend) is estimated separately in the time intervals before and after the selected time step. Not only level (i.e. mean), but also slope of the trend or amplitudes of harmonic components can be estimated in this way.

Variance Intervention: the 'sliding intervention approach'

To see if the start of the hydrological change is observable without an *a priori* knowledge of the timing of the start of forestry operations, we analyse a longer time series by running an estimation procedure we term 'sliding intervention'. For each assumed sliding intervention point, a full estimation of the UC-DHR model is run, with the same parameters except for the changed intervention point. This iterative estimation procedure produces for each time, a magnitude of the step, which can be plotted as a time series to be compared with the estimated uncertainty in the trend.

A version of the UC-DHR model can be purchased as part of the CAPTAIN Toolbox (http://captaintoolbox.co.uk).

RESULTS AND DISCUSSION

We begin by applying the UC-DHR model to the 0·133 km^2 (13·3 ha) Bukit Berembun C1 water budget components, where removal (by selective logging) of 40% of the timber has been shown to result in an inflection in the double mass curve of streamflow (Figure 1(b)). Second, we apply the UC-DHR model to the Afon Hore, where 29% of the forest was clear-felled between December 1985 and October 1987. Lastly, we will apply UC-DHR to the water budget components of the largest catchment, the 37·5 km^2 Upper Hodder, where 22% afforestation (8·25 km^2) of the catchment was undertaken in 1953. The first study has a period of 2·5 years of stream monitoring prior to major forest cover disturbance, the second 10·9 years, and last study, 25 years.

Both the seasonal (i.e. annual and sub-annual cycles) and trend (i.e. inter-annual cycles and drift) components were identified within each time-series. The efficiency (Coefficient of Determination, R^2) of the models fitted to the time series are shown in Table I. As an example, Figure 4 shows the UC-DHR model of all components for the Bukit Berembun C2 'control' catchment streamflow time-series (without Variance Intervention) together with the observed data and model uncertainty. In all subsequent analyses, only the trend (i.e. inter-annual) component is presented and discussed (after the effects of the annual and sub-annual cycles have been taken into account).

Bukit Berembun selective logging study

The modelled trend in streamflow from 1981 to 1987 within the undisturbed (C2) catchment at Bukit Berembun is shown within Figure 5(a). The trend in

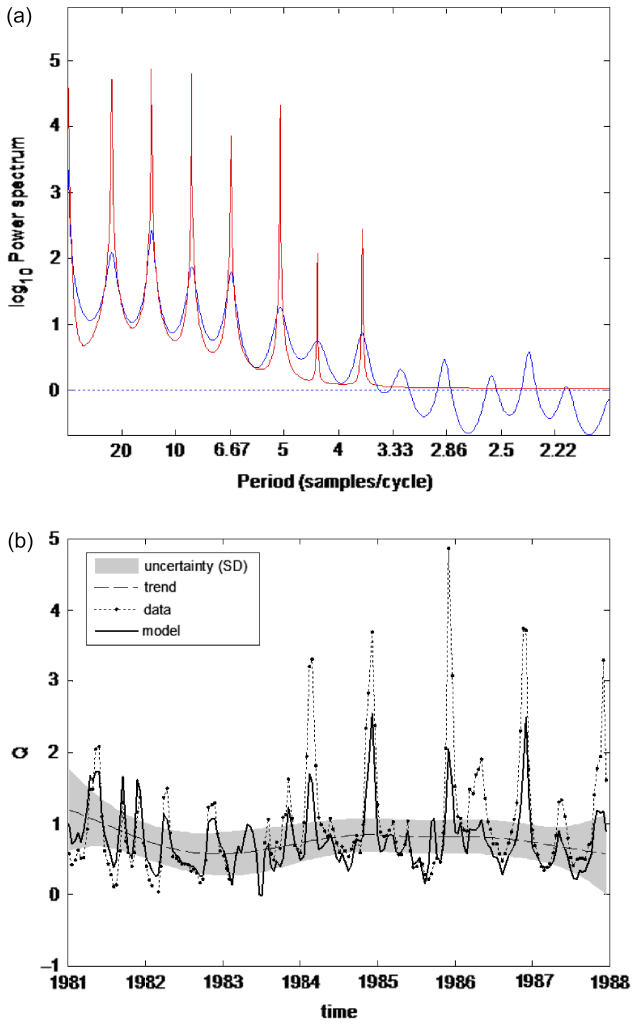

Figure 4. Observed and modelled streamflow for the Bukit Berembun C1 catchment in Peninsular Malaysia. (a) the observed (-) and modelled (· · · ·) power spectrum, and (b) observed streamflow time-series (..●..) and UC-DHR modelled streamflow time-series (-) together with the uncertainty band (± one standard deviation in grey shading). The trend comprising the inter-annual cycles and drift is also shown (—). The *x*-axis is the year, the *y*-axis is the fortnightly streamflow (mm/d)

streamflow within the adjacent catchment disturbed by conventional selective logging (C1) is shown within Figure 5(b). The optimum NVR for the models of the control C2 catchment and logged C1 catchment were similar (i.e. same order of magnitude) at 9×10^{-5} and 5.5×10^{-5}, respectively. The trends for both catchments show a reduced streamflow in 1982/3. UC-DHR modelling of the 1891–1992 rainfall series from the nearby Jelebu meteorological station shows a trough in the rainfall centred on 1983 (Figure 6). Thus, the trough in streamflow seen for both the control and logged catchments is likely to be wholly or partly due to the reduced rainfall input (Wooster *et al.*, 2011). The small difference in the timing of the cycles between the Bukit Berembun data (streamflow or rainfall) and the Jelebu rainfall data probably relates to the 30 km distance between the two rainfall measuring stations (see e.g. Chappell *et al.*, 2001). Visual comparison of the trends for the control C2 (Figure 5(a)) and logged C1 (Figure 5(b)) catchment

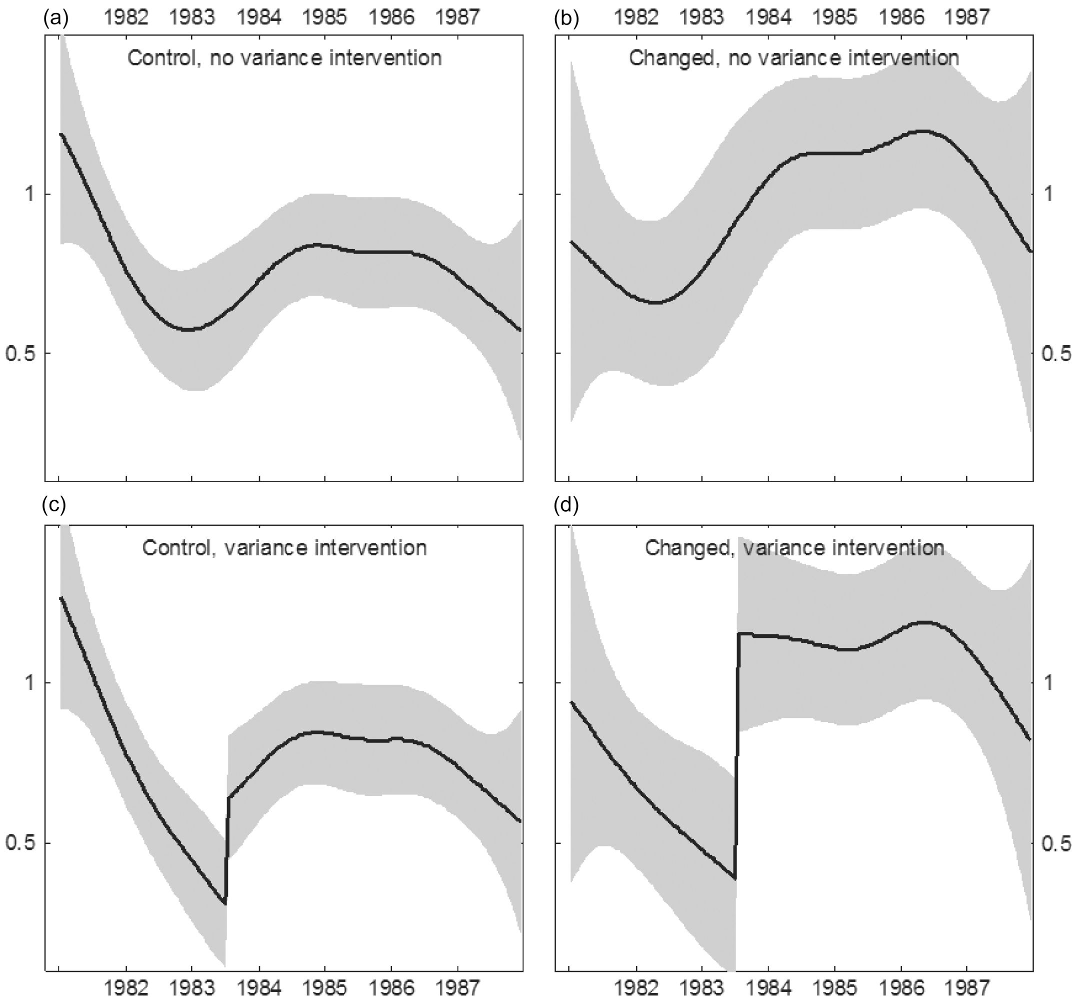

Figure 5. UC-DHR identified inter-annual trend in the Bukit Berembun streamflow time-series for (a) the C2 control catchment (without Variance Intervention), (b) the C1 logged catchment (without Variance Intervention), (c) the C2 control catchment with Variance Intervention at the start of logging in July 1983 (for reference only), and (d) the C1 logged catchment with Variance Intervention at the start of logging in July 1983. The *x*-axis is the year, the *y*-axis is the fortnightly streamflow (mm/d) and the shading encompasses the standard deviation (SD)

streamflows suggest that there is a greater increase in streamflow within the C1 catchment following the start of logging in July 1983 (Figure 5(b)). Thus, the trough in the streamflow trend just before the period of forestry activity has not hidden the differences between the logged and control catchment.

A second simulation of the streamflow for the logged C1 catchment was undertaken, but this time an intervention point (Young and Ng, 1989) was added at the start of the logging operations in July 1983. Figure 5(d) shows the impact of adding an intervention coincident with the start of logging operations. To see whether any step changes in modelled streamflow behaviour could be related to purely rainfall-related changes rather than land-use effects, the model of the undisturbed, control catchment was also run with an intervention point for the same point in time (July 1983: Figure 5(c)). Examination of the modelled streamflow for the undisturbed catchment where the identification routine has sought a step change in streamflow trend starting in July 1983 shows that it is not observable, i.e. the simulated step change (i.e. +0·333 mm/d or 122 mm/yr) is less than the model uncertainty bands (Figure 5(c)). In some contrast, allowing the model to make a step change in the streamflow trend of the logged catchment in July 1983, gives rise to a modelled trend which makes a step increase in July 1983 that is larger than the uncertainty band (Figure 5(d)). Indeed, the step increase in streamflow is much larger than the model uncertainty band and amounts to 0·765 mm/d (Figure 5(d)). Such an increase in streamflow is equivalent to 279 mm/yr in the inter-annual trend. The additional water-yield of 157 mm/yr (i.e. 279−122 mm/yr) is broadly comparable to the 167 mm/yr streamflow increase in the four water-years post-logging calculated by Abdul Rahim and Harding (1992) using a double mass curve. Increases in streamflow following rain forest logging are expected given the measured reductions wet canopy evaporation (Asdak *et al*., 1998; Chappell *et al*., 2001) and expected reductions in transpiration (Wallace and McJannet, 2010) and is clearly seen in paired catchment studies elsewhere in the humid tropics (Bruijnzeel, 1990, 2004; Chappell *et al*., 2004).

To further assess whether the step change in streamflow observed for the logged catchment was related to the land-use change rather than rapid changes in the natural

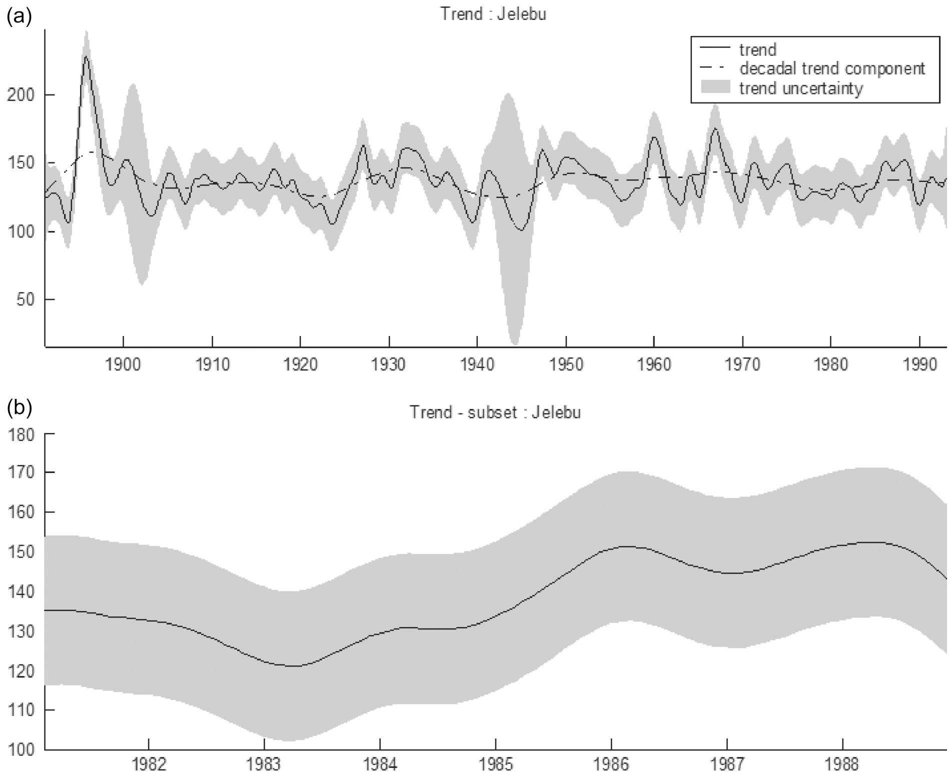

Figure 6. UC-DHR identified inter-annual trend in the Jelebu rainfall from 1891 to 1992 (solid line) and uncertainty band, where (a) shows the whole period, while (b) shows only the period coincident with the Bukit Berembun catchment studies. The *x*-axis is the year, the *y*-axis is the rainfall (mm/month) and the shading encompasses the standard deviation (SD)

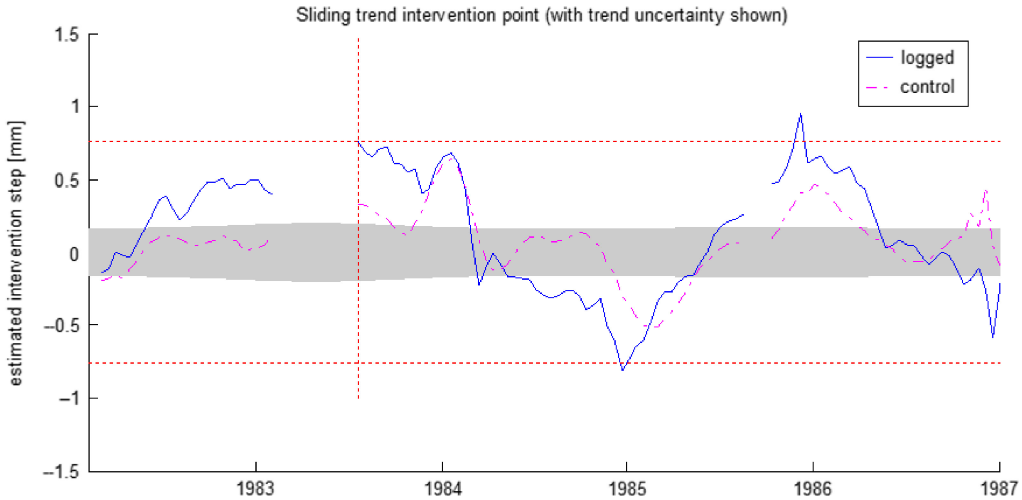

Figure 7. The magnitude of the modelled step-change in Bukit Berembun C1 (-) and C2 (—) streamflow (Q) when the UC-DHR model was run with an intervention point placed at 182 locations in the time-series (i.e. each two-week period of record). The *x*-axis is the year, the *y*-axis is the fortnightly streamflow (mm/d) and the shading encompasses the standard deviation (SD)

climate, the UC-DHR model was run 182 times with the intervention point placed at 182 different points in the time-series. The resultant step changes in the streamflow trend and the model uncertainty are shown in Figure 7. With the exception of an intervention placed in December 1985 (a 7-day break in streamflow records followed by a response to a 67 mm rainstorm), the largest step increase in streamflow coincided with the period immediately after the start of the logging activity; this point is shown with a vertical broken line in Figure 7. This suggests that if the start of the forestry disturbance at this locality had not been known, the best estimate of its timing would indeed have coincided either with a large rainstorm immediately following a data gap or the start of the forestry operations. Furthermore, it indicates that if data from an adjacent, control catchment were not available—the situation normally encountered with large catchments—then forestry-related change (if extensive) may be observable from those changes due to natural climate dynamics. It is, however, worth noting that the 102-year Jelebu rainfall record exhibits even larger inter-annual changes (Figure 6) than seen within

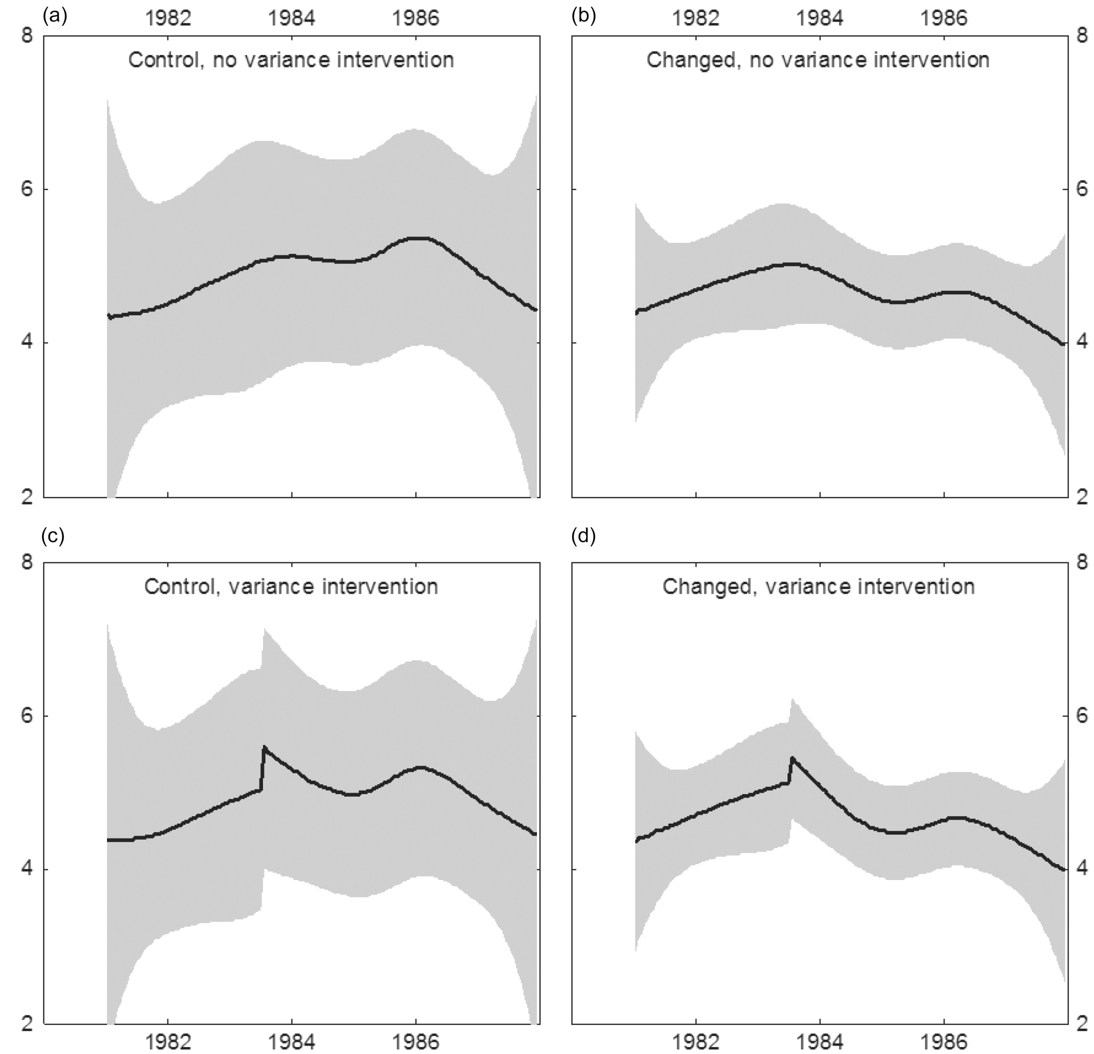

Figure 8. UC-DHR identified inter-annual trend in the Bukit Berembun P-Q time-series for: (a) the C2 control catchment (without Variance Intervention), (b) the C1 logged catchment (without Variance Intervention), (c) the C2 control catchment with Variance Intervention at the start of logging in July 1983 (for reference only), and (d) the C1 logged catchment with Variance Intervention at the start of logging in July 1983. The *x*-axis is the year, the *y*-axis is the fortnightly P-Q (mm/d) and the shading encompasses the standard deviation (SD)

the 8-year record for Bukit Berembun. For example, there is a strong 18–20-year cycle, possibly related to the El Niño Southern Oscillation (ENSO) (Franks and Kuczera, 2002). Such marked changes in the rainfall forcing could mask land-use-related changes occurring at certain times in a multi-decadal record, if only one catchment data-series were to be examined.

For the Bukit Berembun study, the same UC-DHR analysis, with and without the use of an intervention point, was also applied to the P-Q data. Rainfall measured within the Bukit Berembun catchments rather than at Jelebu was used for this analysis. The results are shown in Figure 8. The optimum NVR for the models of the control C2 catchment and logged C1 catchment P-Q were very similar to those for the streamflow models at $9{\cdot}2 \times 10^{-5}$ and $5{\cdot}4 \times 10^{-5}$, respectively. Comparison of the uncertainty bands about the streamflow trends (Figure 5) with those about the P-Q trends (Figure 8) shows that model uncertainty is much greater with the P-Q data. The greater error in the P-Q data will have resulted from the combination of the errors from the two time-series, rainfall and streamflow. Greater data uncertainty obviously makes the identification of change more difficult. As with the modelling of streamflow data for this catchment, application of the intervention point to the P-Q data for the control catchment does not result in a significant step change in the trend (Figure 8(c)). Of greater interest, is the fact that application of the intervention point to the P-Q time-series from the logged catchment, similarly fails to show a step change larger than the uncertainty bands at the start of logging (Figure 8(d)). Thus, the greater noise in the data arising from the combination of the rainfall and streamflow observations (Hudson and Gilman, 1993; Marc and Robinson, 2007) has masked the ability to see forestry-related change in the single P-Q time-series for this catchment study. By applying the intervention point at different locations in the P-Q time-series, the greatest change in the trend appears in mid to late 1985 (Figure 9). This is just ahead of the peak in the long-term, rainfall cycle at Jelebu (Figure 6), indicating that the change in P-Q trend may be purely rainfall-related.

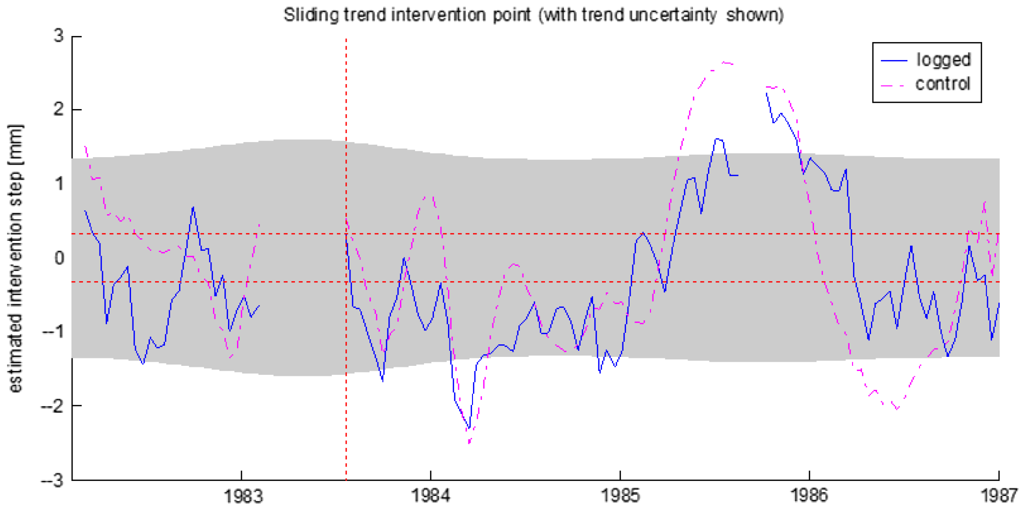

Figure 9. The magnitude and change in the modelled step change in Bukit Berembun logged C1 (-) and control C2 (—) P-Q when the UC-DHR model was run with an intervention point placed at 84 locations in the time series (i.e. each month of record). The *x*-axis is the year, the *y*-axis is the fortnightly P-Q (mm/d) and the shading encompasses the standard deviation (SD)

As the Bukit Berembun C1 catchment is only 13·3 ha in size and underlain by weathered granite (Chappell *et al.*, 2007), it is possible that the usual assumption of a constant subsurface storage (i.e. $\Delta S_{annual} = 0$) for greater than annual periods may not be true. A dynamic subsurface storage over the same inter-annual periods may then mask the forestry-related changes in the actual evaporation that we estimate with the P-Q records.

This case study shows that UC-DHR analysis of a single time-series clearly identifies forestry-related changes in Bukit Berembun streamflow (Q) data, but change within P-Q data is not identifiable, because of the higher uncertainty in the data and possibility of inter-annual storage effects.

Afon Hore partial deforestation study

As the 3·08 km^2 Hore catchment in mid-Wales, UK is 23-fold larger than the Bukit Berembun C1 catchment, and on a mudstone geology likely to have less subsurface storage (Newson, 1976; Neal *et al.*, 1997), inter-annual variations in subsurface storage are less likely to be an issue. Thus, for the Hore catchment, forestry-related change in the P-Q data may be more readily observable. Clear-felling began in early 1985 within the downstream areas of the Hore catchment. Application of the UC-DHR model to the 1975–1997 P-Q data series for the Hore without the use of an intervention point results in a trend exhibiting a 2–3-year cycle, but with a visible reduction in P-Q starting in 1985 (Figure 10(a)).

By applying an intervention point in the modelling at the start of 1985 a step decrease in P-Q much larger than the uncertainty band is observed (Figure 10(b)). A step decrease of 0·88 mm/d (Figure 10(b)) or 321 mm/yr for the second part of the record is shown. For the whole forested area of the 8·7 km^2 Severn catchment, Calder and Newson (1979) calculated 444 mm/yr more P-Q in comparison to the 10·55 km^2 adjacent, grassland Wye catchment for the 1970–1977 period. Using this figure, a 29% removal of the conifer forest at Plynlimon would give a 130 mm/yr reduction in the P-Q. Using a regression model of wet-canopy evaporation and transpiration for the 1974–1984 period, Roberts and Crane (1997) estimated a decrease of 163 mm/year averaged over the 1985–1995 period following the partial clear-felling of the Hore. Additionally, Hudson *et al.* (1999) and Robinson *et al.* (2003) estimated the change in streamflow per unit area (i.e. an alternative to P-Q per unit area) by comparison with the streamflow data from the structure gauging the 1·6 km^2 Upper Hore sub-catchment. Using this method, they found an increase in streamflow of 150 mm/yr within the whole 3·08 km^2 Hore (Hudson *et al.*, 1999; Robinson *et al.*, 2003). Most recently, Robinson and Dupeyrat (2005) estimated an 80 mm/yr reduction in P-Q for the 1983–2000 period relative to the 1974–1982. As noted earlier, conifers in the western uplands of the UK have particularly high rates of wet canopy evaporation (Calder, 1990), so their removal is expected to have large impacts on the total evaporation. The larger step reduction in the P-Q trend from the UC-DHR analysis of a single time-series in comparison to the published Plynlimon studies may, therefore, suggest that the change may be magnified by a step decrease in rainfall occurring at the same time.

As with the intervention modelling of the Bukit Berembun time-series, the UC-DHR model of the Hore data was run with the intervention point placed at different points in the time series, here at 289 different points. The resultant step changes in the P-Q trend and model uncertainty are shown in Figure 10(c). From this analysis it can be seen that one of the largest, broad step reductions in P-Q trend is centred on 1985; the other is centred on 1976 (Figure 10(c)). Thus, while the effect in 1985 could be related, at least in part, to the clear-felling, the effect in 1976 is most likely related to the cycles in the Moel Cynnedd rainfall (Figure 11; Hudson and Gilman, 1993). As wet canopy evaporation is a volumetrically important water loss from conifers in the western uplands of the UK and as is strongly positively correlated with the

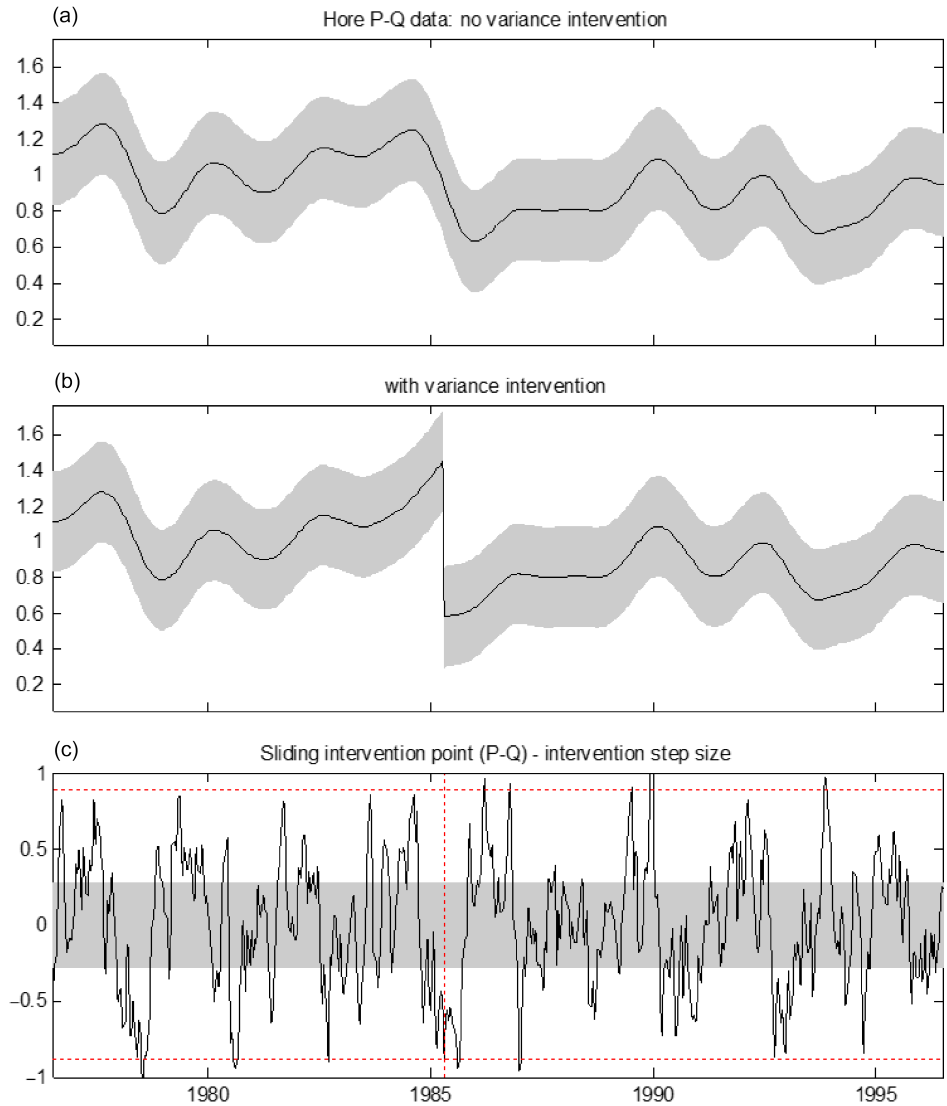

Figure 10. UC-DHR identified inter-annual trend in the Afon Hore P-Q time-series for (a) without Variance Intervention, (b) with Variance Intervention at the start of clearfelling in 1985, and (c) the magnitude and change in the modelled step change in the Afon Hore P-Q when the UC-DHR model was run with an intervention point placed at 289 locations in the time series (i.e. each month of record). The *x*-axis is the year, the *y*-axis is the fortnightly P-Q (mm/d) and the shading encompasses the standard deviation (SD)

rainfall total (Calder, 1990), troughs in the rainfall cycle are likely to give troughs in the wet canopy evaporation, and so troughs in total evaporation and P-Q (compare Figure 11 and Figure 10(a)). Thus, the Hore modelling result could be explained by the effects of partial clear-felling combined with the effect of a rainfall reduction. This conclusion is consistent with the earlier work of Hudson and Gilman (1993) and Hudson *et al.* (1997).

Upper Hodder partial afforestation study

Lastly, the UC-DHR modelling was applied to individual data series from the 37·5 km^2 Upper Hodder catchment where afforestation of 22% of the catchment began in 1953. Walsh (1977) used a linear regression over the 1951–1973 period to show an increase in P-Q (Figure 6.1 in Walsh, 1977), which he attributed to enhanced evaporation by the planted trees.

Application of the UC-DHR model to the P-Q data-series for the Upper Hodder without the use of an

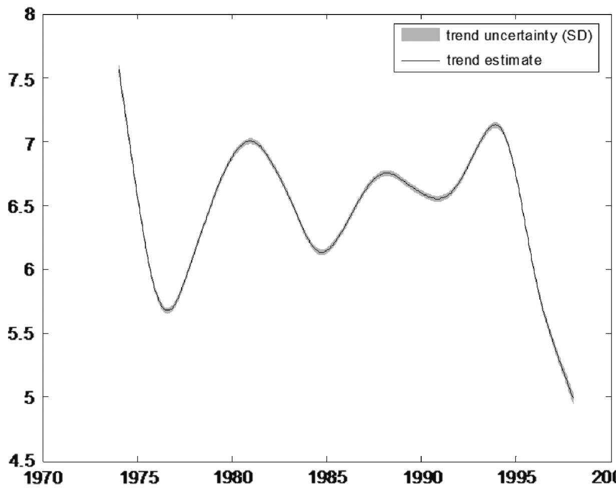

Figure 11. UC-DHR identified inter-annual trend in the Moel Cynnedd rainfall from 1974 to 1997 (solid line) and uncertainty band. The *x*-axis is the year, the *y*-axis is the fortnightly rainfall (mm/d) and the shading encompasses the standard deviation (SD)

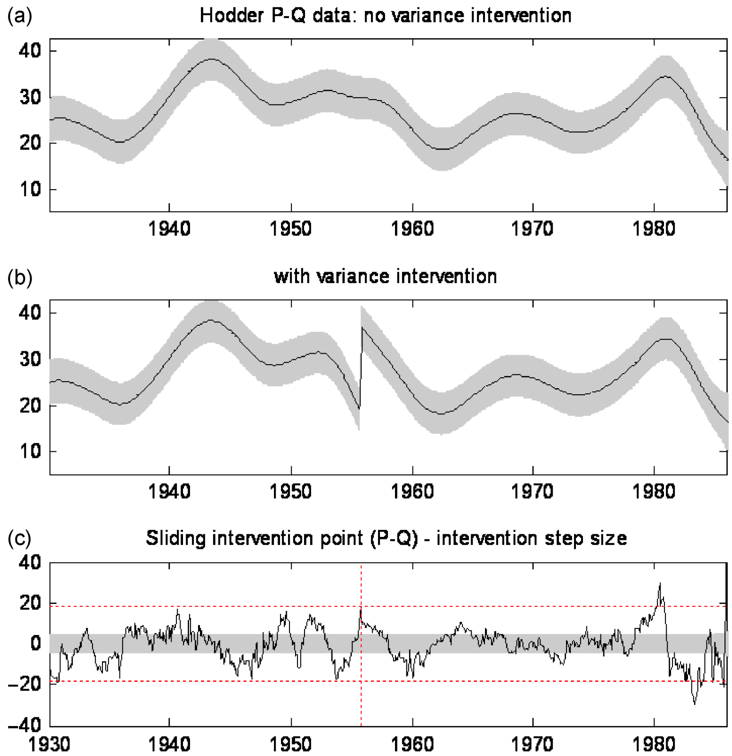

Figure 12. UC-DHR identified inter-annual trend in the Upper Hodder P-Q time-series for (a) without Variance Intervention, (b) with Variance Intervention at the start of afforestation in 1953, and (c) the magnitude and change in the modelled step-change in the Upper Hodder P-Q when the UC-DHR model was run with an intervention point placed at 744 locations in the time-series (i.e. each two-week period of record). The *x*-axis is the year, the *y*-axis is the P-Q (mm/month) and the shading encompasses the standard deviation (SD)

intervention point actually shows a reducing P-Q drift over the 10 years following 1952 (Figure 12(a)), when both short- and longer-term cycles are taken into account. Observing the modelled trend over the whole 1928–1989 period, marked decadal changes in the P-Q can be seen (Figure 12(a)). As 22% afforestation in the 1950s and 15–20% deforestation of this same woodland in the 1980s and 1990s (forest inventory map: Forest Enterprise, personal communication) are the only significant land cover changes in the catchment, the observed decadal changes in P-Q are expected to relate to climatic changes.

By applying an intervention point at the start of afforestation in 1953, modelling of the single time-series does, however, produce a significant step change in the P-Q (Figure 12(b)). P-Q in 1953 does indeed increase relative to the proceeding period, and a step increase of 18·35 mm/month (Figure 12(b)) or 220 mm/year is shown. While the magnitude of the step change is much larger than the uncertainty bands (resulting from data and modelling uncertainty), it is, however, within the range of the P-Q cycles that occur over the full 62-year record. Thus, the step change identified may be solely a function of the climate rather than land-use dynamics. This result is supported by running the UC-DHR model with the intervention point placed at different points in the time series. The resultant magnitude of the step changes in the P-Q trend and its uncertainty are shown in Figure 12(c). It is clear from this analysis, that the step change in 1953 is not the largest step increase; this is seen in 1980 when forest clearances were taking place, and clearances are more likely to have reduced the P-Q.

SYNTHESIS, IMPLICATIONS AND CONCLUSIONS

The model used to analyse the single time series of streamflow or P-Q was the UC-DHR model. This model was seen to be appropriate for this analysis given that it was able to capture most of the streamflow and P-Q dynamics at the seminal experimental sites used for studying forestry impacts on water balances within humid regions (Table I; Figure 4).

Identification of forestry-induced change in a single hydrological time-series

From the wealth of literature published over the past 50 years (e.g. Bosch and Hewlett, 1982; Calder, 1986; Bruijnzeel, 1990, 2001, 2004; Malmer, 1992; Robinson *et al.*, 2003; Chappell *et al.*, 2004), partial removal of forest cover in humid tropical or humid temperate regions is expected to reduce evaporation and increase stream discharge. This is made important by the extensive nature of forest loss across the globe (Watson *et al.*, 2001b). Paired catchment studies and the associated regression analyses or double mass curves (Figure 1(b)) are well established methods to identify change in the water budget of small catchments. This approach is, however, limited by the need for long pre-manipulation observations (Bruijnzeel, 2001) and because ‘control catchments’ with similar physical characteristics and unchanging land-use can be difficult to find, particularly as catchment area increases (NRC, 2008). Given this, methodologies that can identify change within a single hydrological time-series may be valuable.

Using the UC-DHR model we were able to identify step changes attributable to land cover rather than climate changes in a single time-series of discharge from our manipulated tropical catchment (Figure 5(d)) and a single time-series of P-Q from one of our two temperate catchments (Figure 10(a)). While a clear step-reduction in the P-Q at the start of logging was seen within the trend for the temperate catchment (Figure 10(a)), incorporation of the Variance Intervention routine (Young and Ng, 1989) reinforced the attribution of this change to land-use change rather than climate effects.

The analysis of time series records from the three seminal research catchments did however highlight three key issues that affect the ability to observe the effects of land cover changes within single time-series (i.e. where observations from undisturbed, control catchments are not available). The presence of a high degree of data error or the combination of inter-annual cycles in climate and a slow rate of forest change can mask forestry-related changes in single time series of the Bukit Berembun P-Q data (Figure 8(d)) or Hodder P-Q data (Figure 12(c)), respectively.

Change masking by data error

With the Bukit Berembun data, while the ability to identify trends in a nearby undisturbed catchment aided the identification of forestry-induced discharge change in the logged catchment (*cf.* Figure 5(c) and 5(d)), the greater error in the P-Q data (shown by the greater resultant model uncertainty bands) masked any step changes in the single time series attributable to logging (*cf.* Figure 8(c) and 8(d)). The data-related uncertainty associated with the modelled trend was mostly $\pm$300 mm/yr (Figure 8(d)), however, the expected change in P-Q due to tree cutting was only 170 mm/yr (Abdul Rahim and Harding, 1992). Littlewood and Marsh (1996), Hudson *et al.* (1997), Bruijnzeel (2001), Kundzewicz and Robson (2004) and Marc and Robinson (2007) similarly suggested that a high degree of data error relative to the magnitude of change would make hydrological change difficult to identify.

Change masking by climate dynamics

With the Upper Hodder P-Q data, a high degree of inter-annual dynamics is seen prior to significant land cover changes starting with tree planting in 1953 (Figure 12(a)). Marked peaks in the evaporation (P-Q) are seen in, for example, 1944 and 1980, and troughs in, for example, 1936 and 1962 (Figure 12(a)). The maximum amplitude of the decadal cycle from peak to trough is 200 mm/yr (Figure 12(a)), yet the expected increase in evaporation following 22% afforestation of the catchment in 1953 is only 64 mm/yr (i.e. 22% of the 290 mm/yr from Law, 1956, 1957). Thus, the climate-related dynamics (resulting from cycles in rainfall, solar radiation etc.) are perhaps a factor of three larger than the expected afforestation effects in the basin. The effects of these climate dynamics are also seen in the sliding intervention analysis (Figure 12(c)). Wigley and Jones (1985) and our application of UC-DHR to streamflow for a 721 km^2 catchment in Borneo (Chappell *et al.*, 2004) demonstrated that seasonal and inter-annual cycles in rainfall (P) have an amplified effect on streamflow (Q). Thus, large inter-annual changes in rainfall are expected to have a significant impact on P-Q time-series data. Others who have highlighted such climatic obfuscation of forestry impacts on the water budget, include Lee (1970), Hudson and Gilman (1993), Jakeman *et al.* (1993), Hudson *et al.* (1997), Bonell (1998), Bowling *et al.* (2000), Beven (2001), Franks (2002), and Kundzewicz and Robson (2004). Clearly, if all the Upper Hodder basin had been afforested, the step change in evaporation could have been as large as the decadal climate-related cycles and thus more identifiable.

Given that the rate of forest change is likely to be much smaller as catchment area increases from, say, a 1-km^2 forest block to that of a large river (e.g. the 6595 km^2 Muar catchment containing the Bukit Berembun study catchments), the ability to identify forestry impacts on the water budget will reduce. Indeed Seibert and McDonnell (2010) and Zégre *et al.* (2010) recently highlighted this scale issue.

Change masking because of a slower rate of change

A further difficulty is posed by attempts to identify afforestation rather than deforestation impacts. With deforestation of the majority of a gauged catchment, the removal of water-demanding trees in any year can have an immediate impact of the evaporation (Bosch and Hewlett, 1982). In contrast, planting water-demanding trees during one year has a gradually increasing impact over the following decade as the saplings develop to juvenile trees (Swank *et al.*, 1988; Le Maitre and Versfeld, 1997). Thus, afforestation-related change may be more gradual and hence may more difficult to see above those caused by inter-annual climate cycles, particularly if records are short. In the case of the Upper Hodder P-Q data, the analysed P-Q record is 58 years duration, so a change over 10 years might still be considered as a step change.

CONCLUSIONS

In conclusion, the effects of forest change above those attributable to climate dynamics and data error can be seen in single time series of Q and P-Q using techniques such as the UC-DHR model, but this ability depends on the prevailing circumstances (and not on a universally applicable 'threshold': e.g. Sahin and Hall, 1996). Application to three of the most seminal sites for the study of forestry-impacted water balances in humid temperate UK and the humid tropics has yielded several findings regarding the conditions for identifying forestry-induced, hydrological change within single time series. Clearly, further work analysing single time series of streamflow and P-Q for forestry impacts under a wider range of hydro-climatic and forestry conditions, is needed. Moreover, such analyses should incorporate an assessment of the site-specific uncertainties within the observations of streamflow and P-Q.

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REFERENCES

Abdul Rahim N. 1990. *The Effects of Selective Logging Methods on Hydrological Parameters in Peninsular Malaysia*. Ph.D. thesis. University of Wales: Bangor.

Abdul Rahim N, Harding D. 1992. Effects of selective logging methods on water yield and streamflow parameters in Peninsular Malaysia. *Journal of Tropical Forest Science* **5**: 130–154.

Anderton S, Latron M, Gallart F. 2002. Sensitivity analysis and multi-response, multi-criteria evaluation of a physically based distributed model. *Hydrological Processes* **16**: 333–353.

Archer DR, Fowler HJ. 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. *Hydrology and Earth System Sciences* **8**: 47–61.

Asdak C, Jarvis PG, van Gardingen P, Fraser A. 1998. Rainfall interception loss in unlogged and logged forest areas of Central Kalimantan, Indonesia. *Journal of Hydrology* **206**: 237–244.

Bates CG, Henry AJ. 1928. Forests and streamflow at Wagon Wheel Gap, Colorado. Final Report. *Monthly Weather Review Supplement* **30**: 1–79.

Beven KJ. 2001. On fire and rain (or predicting the effect of change). *Hydrological Processes* **15**: 1397–1399.

Bonell M. 1998. Possible impacts of climate variability and change on tropical forest. *Climate Change* **39**: 215–272.

Bonell M. 1999. Tropical forest hydrology and the role of the UNESCO International Hydrological Programme. *Hydrology and Earth System Sciences* **3**: 451–461.

Bormann FH, Likens GE, Melillo JM. 1977. Nitrogen budget for an aggrading northern hardwood forest ecosystem. *Science* **196**: 981–983.

Bosch JM, Hewlett JD. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* **55**: 3–23.

Bowling LC, Storck P, Lettenmaier DP. 2000. Hydrologic effects of logging in western Washington, United States. *Water Resources Research* **36**: 3223–3240.

Bruijnzeel LA. 1990. *Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review*. UNESCO: Paris; p. 224.

Bruijnzeel LA. 2001. Forest hydrology. In *The Forests Handbook*, Evans J (ed). Blackwell: Oxford; pp. 301–343.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture Ecosystems and Environment* **104**: 185–228.

Calder IR. 1986. The influence of land-use on water yield in upland areas of the UK. *Journal of Hydrology* **88**: 201–211.

Calder IR. 1990. *Evaporation in the uplands*. Wiley: Chichester; p. 148.

Calder IR, Newson MD. 1979. Land use and upland water resources in Britain—a strategic look. *Water Resources Bulletin* **16**: 1628–1639.

Calder IR, Newson MD, Walsh PD. 1982. The application of catchment, lysimeter and hydrometeorological studies of coniferous afforestation in Britain to land-use planning and water management. In *Proceedings of the Symposium on Hydrological Research Basins*. Bern; 1852–1983.

Chahine MT. 1992. The hydrological cycle and its influence on climate. *Nature* **359**: 373–380.

Chappell NA, Bidin K, Tych W. 2001. Modelling rainfall and canopy controls on net-precipitation beneath selectively-logged tropical forest. *Plant Ecology* **153**: 215–229.

Chappell NA, McKenna P, Bidin K, Douglas I, Walsh RPD. 1999. Parsimonious modelling of water and suspended-sediment flux from nested-catchments affected by selective tropical forestry. *Philosophical Transactions of the Royal Society of London Series B* **354**: 1831–1846.

Chappell NA, Nik AR, Yusop Z, Tych W, Kasran B. 2004. Spatially-significant effects of selective tropical forestry on water, nutrient and sediment flows: a modelling-supported review. In *Forests, Water and People in the Humid Tropics*, Bonell M, Bruijnzeel LA (eds). Cambridge University Press: Cambridge; pp. 513–532.

Chappell NA, Sherlock M, Bidin K, Macdonald R, Najman Y, Davies G. 2007. Runoff processes in Southeast Asia: role of soil, regolith and rock type. In *Forest Environments in the Mekong River Basin* Sawada H, Araki M, Chappell NA, LaFrankie JV, Shimizu A (eds). Springer Verlag: Tokyo; pp. 3–23.

Eckhardt K, Bruer L, Frede HG. 2003. Parameter uncertainty and the significance of simulated land use change effects. *Journal of Hydrology* **273**: 164–176.

Foley JA, Botta A, Coe MT, Costa MH. 2002. El Nino-Southern Oscillation and the climate, ecosystems and rivers of Amazonia. *Global Biogeochemical Cycles* **16**: 1132.

Ford CR, Hubbard RM, Kloeppel BD, Vose JM. 2007. A comparison of sap flux-based evapotranspiration estimates with catchment-scale water balance. *Agricultural and Forest Meteorology* **145**: 176–185.

Franks SW. 2002. Assessing hydrological change: deterministic general circulation models or spurious solar correlation? *Hydrological Processes* **16**: 559–564.

Franks SW, Kuczera G. 2002. Flood frequency analysis: evidence and implications of secular climate variability, New South Wales. *Water Resources Research* **38**: 1062.

Fylde Water Board. 1966. *Some Comments and Figures Relating to Evaporation Tanks and Pans*. Fylde Water Board: Slaidburn; p. 4.

Gregory KJ, Walling DE. 1973. *Drainage Basin Form and Process*. Wiley: New York.

Harr RD, McCorison FM. 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in western Oregon. *Water Resources Research* **15**: 90–94.

Harvey AC. 1984. A unified view of statistical forecasting procedures. *Journal of Forecasting* **3**: 245–283.

Harvey AC. 1989. *Forecasting structural time series models and the Kalman Filter*. Cambridge University Press: Cambridge; p. 554.

Hewlett JD, Lull HW, Reinhart KG. 1969. In defense of experimental watersheds. *Water Resources Research* **5**: 306–316.

Hibbert AR. 1967. Forest treatment effects in water yield. In *International Symposium on Forest Hydrology*, Sopper WE, Lull HW (eds). Pergamon Press: New York; pp. 527–543.

Hudson JA, Crane SB, Blackie JR. 1997. The Plynlimon water balance 1969–1995: the impact of forest and moorland vegetation on evaporation and streamflow in upland catchments. *Hydrology and Earth System Science* **1**: 409–428.

Hudson JA, Gilman K. 1993. Long-term variability in the water balances of the Plynlimon catchments. *Journal of Hydrology* **143**: 355–380.

Hudson JA, Gilman K, Robinson M, Leeks GJL, Neal C, Calder IR, Reynolds B, Beaumont WRC. 1999. *Land-use and Water Issues in the Uplands: the Plynlimon Story*. Institute of Hydrology: Wallingford.

Institute of Hydrology. 1976. *Water Balance of the Headwater Catchments of the Wye and Severn*. *Institute of Hydrology Report* No. 33. Institute of Hydrology: Wallingford; p. 62.

Jakeman AJ, Littlewood IG, Whitehead PG. 1993. An assessment of the dynamic response characteristics of streamflow in the Balquhidder catchments. *Journal of Hydrology* **145**: 337–355.

Jones JA, Grant GE. 1996. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon. *Water Resources Research* **32**: 959–974.

Kiem AS, Franks SW. 2001. On the identification of ENSO-induced rainfall and runoff variability: a comparison of methods and indices. *Hydrological Sciences Journal* **46**: 715–727.

Kirby C, Newson MD, Gilman K. 1991. *Plynlimon Research: The First Two Decades*. Institute of Hydrology: Wallingford; p. 188.

Koopman SJ, Harvey AC, Doornik JA, Shephard N. 2000. *STAMP 6·0: structural time series analyser, modeller and predictor*. Timberlake Consultants Press: London.

Kundzewicz ZW, Robson AJ. 2004. Change detection in hydrological records—a review of the methodology. *Hydrological Science Journal* **49**: 7–19.

Law F. 1956. Effect of afforestation upon the yield of water catchment areas. *Journal of the British Waterworks Association* **38**: 489–494.

Law F. 1957. Measurement of rainfall, interception and evaporation losses in a plantation of Sitka spruce trees. *IUGG/IASH General Assembly of Toronto, Volume 2*; 397–411.

Law F. 1964. *Aspects of Water Losses*. Diploma thesis. University of Newcastle: Newcastle-upon-Tyne; p. 40.

Lee R. 1970. Theoretical estimates versus forest water yield. *Water Resources Research* **6**: 327–344.

Le Maitre DC, Versfeld DB. 1997. Forest evaporation models: relationships between stand growth and evaporation. *Journal of Hydrology* **193**: 240–257.

Littlewood IG, Marsh TJ. 1996. A re-assessment of the monthly naturalised flow record for the River Thames at Kingston since 1983 and the implications for the relative severity of historic droughts. *Regulated Rivers: Research and Management* **12**: 13–26.

Lukey BT, Sheffield J, Bathurst JC, Hiley RA, Mathys N. 2000. Test of the SHETRAN technology for modelling the impact of reforestation on badlands runoff and sediment yield at Draix, France. *Journal of Hydrology* **235**: 44–62.

Ma X, Xu JC, van Noordwijk M. 2010. Sensitivity of streamflow from a Himalayan catchment to plausible changes in land cover and climate. *Hydrological Processes* **24**: 1379–1390.

Madden RA, Julian PR. 1971. Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of Atmospheric Science* **28**: 702–708.

Madden RA, Julian PR. 1972. Description of global—scale circulation cells in the tropics with a 40–50 day period. *Journal of Atmospheric Science* **29**: 1109–1123.

Madden RA, Julian PR. 1994. Observations of the 40–50 day tropical oscillation: a review. *Monthly Weather Review* **122**: 814–837.

Malmer A. 1992. Water-yield changes after clear felling tropical rainforest and establishment of forest plantation in Sabah, Malaysia. *Journal of Hydrology* **134**: 77–94.

Marc V, Robinson M. 2007. The long-term water balance (1972–2004) of upland forestry and grassland at Plynlimon, mid-Wales. *Hydrology and Earth System Sciences* **11**: 44–60.

Morton FI. 1985. What are the limits of forest evaporation—reply. *Journal of Hydrology* **82**: 184–192.

Neal C, Robson AJ, Shand P, Edmund WM, Dixon AJ, Buckle DK, Hill S, Harrow M, Neal M, Wilkinson J, Reynolds B. 1997. The occurrence of groundwater in the Lower Palaeozoic rocks of upland Central Wales. *Hydrology and Earth System Sciences* **1**: 3–18.

Newson MD. 1976. *The physiography, deposits and vegetation of the Plynlimon catchments*. Report Number 30. Institute of Hydrology: Wallingford; p. 59.

Newson MD, Calder IR. 1989. Forests and water resources: problems of prediction on a regional scale. *Philosophical Transactions of the Royal Society of London* **324**: 283–298.

Ng CN, Young PC. 1990. Recursive estimation and forecasting of non-stationary time series. *Journal of Forecasting* **9**: 173–204.

NRC. 2008. *Hydrologic effects of a changing forest landscape*. National Academies Press: Washington DC; p. 168.

O'Connell, E, Ewen J, O'Donnell G, Quinn P. 2007. Is there a link between agricultural land-use management and flooding? *Hydrology and Earth System Sciences* **11**: 96–107.

Ovington JD. 1954. A comparison of rainfall in different woodlands. *Forestry* **27**: 41.

Patric J, Reinhart K. 1971. Hydrologic effects of deforesting two mountain watersheds in West Virginia. *Water Resources Research* **7**: 1182–1188.

Penman HL. 1963. *Vegetation and Hydrology*. Commonwealth Agricultural Bureaux: Farnham; p. 125.

Polcher J. 1995. Sensitivity of tropical convection to land-surface processes. *Journal of Atmospheric Sciences* **52**: 3143–3161.

Rajendran K, Nanjundiah RS, Srinivasan J. 2002. The impact of surface hydrology on the simulation of tropical intraseasonal oscillation in NCAR (CCM2) atmospheric GCM. *Journal of the Meteorological Society of Japan* **80**: 1357–1381.

Roberts G, Crane SB. 1997. The effects of clear-felling established forestry on stream-flow losses from the Hore sub-catchment. *Hydrology and Earth System Sciences* **1**: 477–482.

Robinson M, Cognard-Plancq AL, Cosandey C, David J, Durand P, Fuhrer HW, Hall R, Hendriques MO, Marc V, McCarthy R, McDonnell M, Martin C, Nisbet T, O'Dea P, Rodgers M, Zollner A. 2003. Studies of the impact of forests on peak flows and baseflows: a European perspective. *Forest Ecology and Management* **186**: 85–97.

Robinson M, Dupeyrat A. 2005. Effects of commercial timber harvesting on streamflow regimes in the Plynlimon catchments, mid-Wales. *Hydrological Processes* **19**: 1213–1226.

Roy SB, Avissar R. 2002. Impact of land use/land cover change on regional hydrometeorology in Amazonia. *Journal of Geophysical Research-Atmospheres* **107**(D20): 8037.

Sahin V, Hall MJ. 1996. The effects of afforestation and deforestation on water yields. *Journal of Hydrology* **178**: 293–309.

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. 1999. A dipole mode in the tropical Indian Ocean. *Nature* **401**: 360–363.

Santing G. 1953. Discussion on hydrological measurements. *Journal of the Institution of Water Engineers* **7**: 245.

Schulze RE. 2000. Modelling hydrological responses to land use and climate change: a southern African perspective. *Ambio* **29**: 12–22.

Searcy JK, Hardison CH. 1960. *Double-mass curves*. Water Supply Paper 1541-B. USGS: Washington; p. 66.

Seibert J, McDonnell JJ. 2010. Land-cover impacts on streamflow: a change-detection modelling approach that incorporates parameter uncertainty. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **55**: 316–332.

Shuttleworth WJ. 1988. Macrohydrology: The new challenge for process hydrology. *Journal of Hydrology* **100**: 31–56.

Swank WT, Swift LW, Douglass J. 1988. Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In *Forest Hydrology and Ecology at Coweeta*, Swank WT, Crossley DA, Jr (eds). Springer-Verlag: New York; pp. 297–312.

Thang HC, Chappell NA. 2004. Minimising the hydrological impact of forest harvesting in Malaysia's rainforests. In *Forests, Water and People in the Humid Tropics*, Bonell M, Bruijnzeel LA (eds). Cambridge University Press: Cambridge; pp. 852–865.

Todd DK. 1980. *Groundwater Hydrology*. Wiley: New York; p. 535.

Trigo RM, Pozo-Vazquez D, Osborn TJ, Castro-Diez Y, Gamiz-Fortis S, Esteban-Parra. MJ. 2004. North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology* **24**: 925–944.

Tych W, Chappell NA. 2003. New modelling techniques in the analysis of tropical climatic and hydrological data. In *Conference on Monsoon Environments: Agricultural and Hydrological Impacts of Seasonal Variability and Climate Change (24–28 March 2003)*, ICTP: Trieste.

Wallace J, McJannet D. 2010. Processes controlling transpiration in the rainforests of north Queensland, Australia. *Journal of Hydrology* **384**: 107·117. DOI:10.1016/j.jhydrol.2010.01.015.

Walsh PD. 1977. *The Practical Analysis and Operation of Multi-Source Water Supply Systems with Particular Reference to the Lancashire Conjunctive Use Scheme.* Ph.D. thesis, Birmingham University: Birmingham.

Wang YH, Yu PT, Xiong W, Shen ZX, Guo MC, Shi ZJ, Du A, Wang LM. 2008. Water-yield reduction after afforestation and related processes in the semiarid Liupan Mountains, Northwest China. *Journal of the American Water Resources Association* **44**: 1086–1097.

Watson F, Vertessy R, McMahon T, Rhodes B, Watson I. 2001a. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. *Forest Ecology and Management* **143**: 189–204.

Watson FGR, Vertessy RA, Grayson RB. 1999. Large-scale modelling of forest hydro-ecological processes and their long term effect on water yield. *Hydrological Processes* **13**: 689–700.

Watson RT, Noble IR, Bolin B, Ravindranath DJ, Dokken DJ. 2001b. *Land Use, Land-use Change and Forestry: A Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge; p. 388.

Wei XH, Sun G, Liu SR, Jiang H, Zhou GY, Dai LM. 2008. The forest-streamflow relationship in China: A 40-year retrospect. *Journal of the American Water Resources Association* **44**: 1076–1085.

West M, Harrison PJ, Migon HS. 1985. Dynamic generalised linear models and Bayesian forecasting. *Journal of the American Statistical Association* **80**: 73–96.

Wigley TML, Jones PD. 1985. Influences of precipitation and direct CO_2 effects on streamflow. *Nature* **314**: 149–152.

Wilk J, Hughes DA. 1992. Simulating the impacts of land-use and climate change on water resource availability for a large south Indian catchment. *Hydrological Sciences Journal* **47**: 19–30.

Wilson KB, Hanson PJ, Mulholland PJ, Badocchi DD, Wullschleger SD. 2001. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. *Agricultural and Forest Meteorology* **106**: 153–168.

Wooster MJ, Perry GLW, Zoumas A. 2011. Fire, drought and El Niño relationships on Borneo during the pre-MODIS era (1980–2000). *Biogeosciences Discussions* **8**: 975–1013.

Young PC. 1998. Data-based mechanistic modelling of environmental, ecological, economic and engineering systems. *Environmental Modelling and Software* **13**: 105–122.

Young PC. 2001. Data-Based Mechanistic modelling and validation of rainfall-flow processes. In *Model Validation: Perspectives in Hydrological Science*, Anderson MG, Bates PD (eds). Wiley: Chichester; pp. 117–161.

Young PC, Ng CN. 1989. Variance intervention. *Journal of Forecasting* **8**: 399–416.

Young PC, Pedregal DJ, Tych W. 1999. Dynamic harmonic regression. *Journal of Forecasting* **18**: 369–394.

Zégre N, Skaugset AE, Som NA, McDonnell JJ, Ganio LM. 2010. In lieu of the paired catchment approach: Hydrologic model change detection at the catchment scale. *Water Resources Research* **46**: W11544, 10.1029/2009wr008601.

