Response of Emergent Behaviour of Headwater Catchments to Environmental Change

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1. INTRODUCTION

Emergent behaviour of hydrological processes at the catchment scale often results in simple and predictable functional characteristics which are underpinned by complex, heterogeneous processes at the small scale. It is unclear how such small-scale processes are affected by long-and short-term perturbations in temporally variable forcing factors. For example, identification of the impacts of land use changes can be confounded by other factors such as climatic variability and longer-term aspects of environmental change. These complications are usually exacerbated by a lack of long-term data sets to assess the relative importance of different drivers of hydrological and hydrochemical change. This leads to uncertainty in how emergent behaviour will change and how hydrology and hydrochemistry will respond at the larger scale. A powerful resource in improving predictions of non-linear responses in hydrological behaviour is applying advanced statistical analysis to long-term data sets of conservative tracers, particularly in gauged catchments that are subject to marked environmental change. Changes in tracer behaviour can provide an integrated synthesis into the emergent response of system functioning and its non-linear characteristics, which helps underpin predictions in ungauged basins.

Here, we present the analysis of long-term tracer data in two small (ca. 1km^2) experimental catchments in the Scottish highlands. Long-term (20 year, weekly) time-series analyses of two tracers are used to assess changes in emergent catchment behaviour. Alkalinity of stream waters was used to examine how the contribution of different hydrological sources changed over the study period in response to climatic variability, forestry and reduced acid deposition. In addition, chloride input-output time series were used to assess the impact on mean catchment residence times.

Our objectives are:
(i) To quantitatively assess temporal changes in chemically-defined end member composition of soil and groundwaters that are the main sources of runoff

(ii) To use time varying end members (with uncertainty) applying non-linear methods to undertake hydrograph separation to assess any changes in source contributions as a result of environmental change

(iii) To evaluate the effects of environmental change on catchment function in terms of mean residence times.

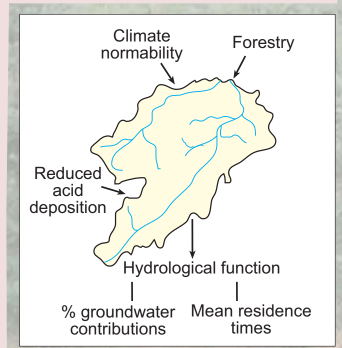

Figure 1: Diagnostic characteristics to assess hydrological impacts of environmental change.

2. STUDY AREA AND DATA

- Loch Ard area, Central Scotland: commercial forestry with Sitka Spruce (*Picea Sitchensis*) since 1950's
- Geology: dominated by impermeable Dalradian metamorphic rocks
- Soils: poorly drained gleyed soils (peaty/humic gleys to more minerogenic gleys, Fig 2a) - close to saturation throughout most years and therefore hydrologically responsive in precipitation events
- Long-term (20 yrs) hydrological and hydrochemical data sets available for two almost entirely (ca 95%) afforested catchments: Burn 10 (B10, 0.9 km^2) and Burn 11 (B11, 1.4 km^2) (Table 1)
- Air pollution legislation targeting acid emissions has improved the quality of precipitation, resulting in a marked reduction in acid deposition
- Forest operations led to sequential felling (Fig.2b)
- Marked climatic variability

	Burn 10	Burn 11
Area (km^2)	0.9	1.4
Mean annual flow (mm)*	1660	1674
Mean annual precipitation (mm)*	1978	1978
Topography		
Mean elevation (m)	166	183
Min elevation (m)	99	99
Max elevation (m)	221	282
Mean slope (°)	11	9
Max slope (°)	41	39
HOST Classes [%]		
29 (Peats)	0	1.7
14 (Poorly drained mineral non-calcareous gleys and humic gleys)	0	21.7
24 (Poorly drained non-calcareous, humic and peaty gleys)	100	76.6

Table 1: Summarised catchment characteristics for the two stream sites investigated (*1988-2003).

Plate 1: Catchment overview.

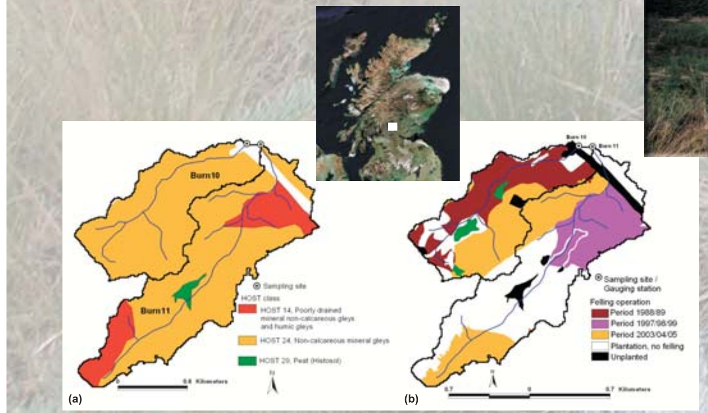

Figure 2: (a) HOST (Hydrology of Soil Types) classes for the two sampling sites investigated: Burn 10 and Burn 11; (b) Areas and time periods of felling operations.

3. TEMPORAL CHANGE IN EMERGENT HYDROCHEMISTRY

3.1 Long-term changes in hydrochemistry

- Long-term time series integrate effects of flow and biogeochemistry on stream water chemistry reflecting inter-annual variability in climate, reduced acid deposition and land use change (Tetzlaff et al., 2007a)
- This is reflected in annual variability of alkalinity (Fig. 3): alkalinity tends to be higher in summer low flows and lower during winter storm events.
- Increasing trend in alkalinity over the period of record, which is most clear in B10, corresponding to declining levels of acid deposition
- DOC concentrations vary seasonally in relation to flows and temperatures (Fig. 4)
- Increasing amplitude of seasonal variations leads to long-term increase in concentrations of DOC
- Hypothesis: combined effects of warmer and drier years over the latter decade in period of record and effects of forestry may both play a role

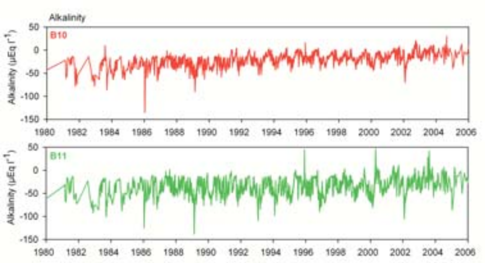

Figure 3: Long-term variation in Alkalinity for B10 and B11.

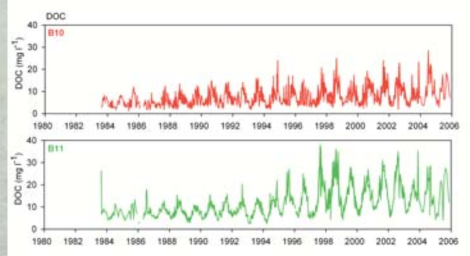

Figure 4: Long-term variation in DOC for B10 and B11.

3.2. Chemical-based hydrograph separation using statistical methods for defining end members

The temporal changes in concentration-discharge relationships resulting from decreased acid deposition were described via a statistical model fitting year-specific non-linear (Weibull) curves via random effects (Fig. 5) (Brewer et al., 2005). From this fitted model, and using a statistical model-based version of the annual stream hydrograph, the distribution of stream alkalinity was estimated (Fig. 6). This facilitated temporal differences in catchment-scale hydrological source contributions (specifically groundwater) to be related to the temporal changes in end member composition, which in turn allowed classic two-component mixing models (Tetzlaff et al., 2007a).

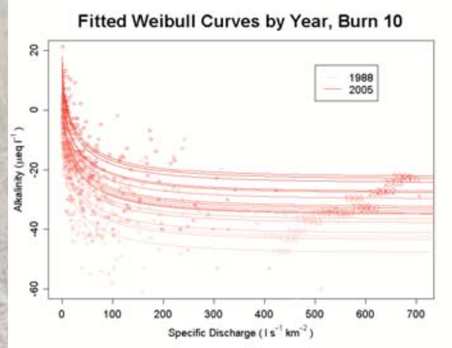

Figure 5: Year specific Weibull curves showing temporal changes in flow alkalinity relationships, example shown Burn 10.

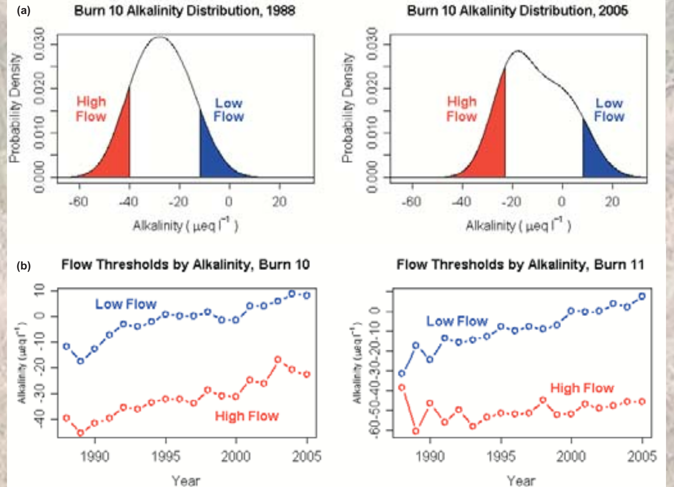

Figure 6: The distribution of flow was modelled using a non-parametric density estimate on a year-by-year basis. The Q5 and Q95 points were calculated for these flow distributions and the fitted Weibull curve was used to map these points onto the alkalinity scale; these are the thresholds visible in Figure 6(a). Figure 6(b) Temporal changes in soil and groundwater end member, determined as flow thresholds by alkalinity, in Burn 10 and Burn 11.

4. IMPLICATIONS FOR WATER SOURCES

- In both catchments, groundwater contributions are uncertain, but comprise ca. 30-40% of annual flows over the period
- Generally, percentage groundwater contributions are highest in low flow years and lowest in wet years
- Some evidence for slightly reduced groundwater contributions following felling operations, but unclear
- Main driver appears to be climatic variability

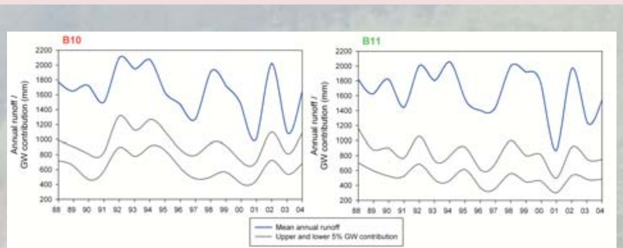

Figure 7: Chemically based hydrograph separation from non-linear methods showing annual runoff and predicted range of groundwater contribution.

5. IMPLICATIONS FOR CATCHMENT MEAN RESIDENCE TIMES

- Use of long-term records of chloride concentrations in precipitation and streamwaters in lumped parameter residence time models
- Weighted monthly chloride inputs Cl_{in} in precipitation were transformed by convolution integration into output Cl_{out} : $Cl_{out}(t)=\int_0^\infty g(t')Cl_{in}(t-t')dt'$

With $g(t')$: system response function specifying the transit time distribution of water through the system; t: calendar time, t': transit time.

- This provided the basis for using both Exponential Models (EM) and Exponential Piston Flow Models (EPM) for estimation of mean residence times
- At Loch Ard, precipitation is relatively evenly distributed in most years and soil moisture deficits are relatively modest: meaningfully defining "baseflow" is impossible
- Thus, precipitation samples weighted according to mean monthly precipitation amounts (adjusted for evaporation in the summer: a recharge fraction proportional to any interception losses and soil moisture deficits was estimated) to predict streamflow concentrations at monthly timesteps.
- Estimation of effect of dry and occult deposition on Cl inputs: annual weighted precipitation concentrations were multiplied by an enhancement factor that ensured that it equalled weighted Cl concentrations outputs
- Cl in precipitation exhibits marked seasonality; being high in winter storms (fronts from the Atlantic bring salt-laden precipitation) and lower in summer In most years these seasonal patterns in rainfall are clearly reflected in the streamwater response, implying flashy catchments that are very responsive to rainfall
- Chloride input-output time series highlighted non-stationarity in catchment mean residence times (which ranged between 2-11 months for individual years) and corresponding residence time distributions
- Both EM and EPM models give feasible predictions, though years without marked seasonal variability in weighted Cl inputs (either because of ow concentrations or rainfall amounts) showed the poorest fit (Fig.8)
- B10: MRTs of 2-6 months for the EM and 6-9 months for the EPM
- B11: MRTs of 2-8 months for the EM and 8-10 months for the EPM Slightly higher estimates for B11 are consistent with the catchment characteristics: reduction of transit times due to steeper gradients in B10 and coverage of deeper HOST class 14 soils in B11 (greater soil moisture storage and groundwater recharge)
- Little evidence of any forestry effect on residence times – at least at scales >1 month – as estimates for individual years showed no effects, which was consistent with runoff data and flow path partitioning.

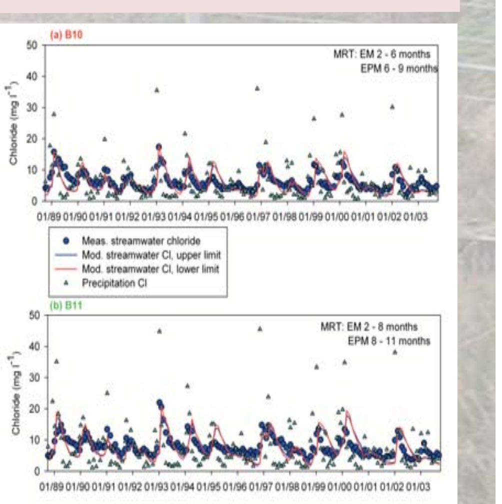

Figure 8: Simulated and actual weighted mean monthly Cl concentrations and mean residence time estimates based on convolution integral-based Exponential Model (EM) and Exponential Piston Flow Model (EPM).

6. CONCLUSION

- Long-term hydrochemistry data sets show effects of forestry on of stream water quality and hydrological catchment response in a wider framework climatic variability and environmental change
- Underlying longer-term climatic/deposition changes and short-term land use disturbances, inter-annual climatic variability has major influence on driving hydrology and biogeochemistry
- Study emphasises importance of temporal differences in catchment residence times in relation to annual water balances, clustering of wet and dry years, and precipitation distributions throughout the year.
- Longer term data indicate that characteristic shape and exponent of catchment residence time are probably non-stationary on an annual basis and vary in relation to precipitation and tracer loadings, precipitation distribution and antecedent soil moisture conditions
- Different residence time distributions can occur in different years, or periods of years, depending upon prevailing and antecedent climatic conditions, which raises the question: can the mean residence times of a watershed be viewed as a fixed characteristic?
- "Average" mean residence times estimated over longer periods, assume a degree of stationarity in both the residence times and residence time distribution, which may not be appropriate as the importance of climatic change and variability increases as predicted by GCMs
- Additionally, hydrological connectivity between catchment land management and downstream ecosystem response to hydrological and biogeochemical change (c.f. Tetzlaff et al., 2007b) - requires integrated hydroecological investigations that upscale to larger river basis to understand the impacts of small scale land management impacts on ecological status of larger freshwater systems (Tetzlaff et al., 2007c; Tetzlaff et al., 2008)

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