A Method for Determining the Impact of Soil and Snow Storage on the Hydrologic Response of Forested Catchments

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Abstract To regionalise hydrologic response, one must first quantify the mechanisms controlling it in the region of interest. One of these mechanisms is the storage of water in soil and snow. Quantifying the effect of soil and snow storage on hydrologic response can be difficult, with direct measurements costly and often inaccurate. We present a method for determining the effect of soil and snow storage on hydrologic response through examining auto- and cross-correlations of precipitation and streamflow. This method is applied to forested catchments in four regions of the United States : Oregon (H J Andrews Experimental Forest); New Hampshire (Hubbard Brook Experimental Forest); North Carolina (Coweeta Hydrologic Laboratory); and Puerto Rico (Luquillo Experimental Forest). These sites represent a range of climatologies, landscapes and vegetation types. The results show that when applied at a monthly timestep, this method produces an estimate of both the magnitude and duration of the catchment water store. In addition, it allows us to distinguish between soil and snow moisture storages. When applied at a daily timestep, this method produces an estimate of the catchment response time to a precipitation event. This response time can be thought of as the catchment 'buffering capacity'. It may be a useful indicator of the potential of a catchment to produce peakflow (flood) events.

1. INTRODUCTION

The streamflow hydrograph reflects how precipitation inputs are modified by various storages and losses in a catchment. The relationship between the streamflow hydrograph and precipitation inputs is a measure of the importance and timing of intermediate storages in soil and snow, and losses from evapotranspiration at a given time scale. Therefore, we hypothesise that streamflow will be correlated with the variability of precipitation inputs at a range of temporal scales. The strength of this relationship will reflect between-catchment differences in storage and water use by vegetation.

Temporal autocorrelations in precipitation at the monthly time scale reflect seasonal differences in precipitation; at the daily time scale, these autocorrelations reflect the duration of storm events. On the other hand, temporal cross-correlations between precipitation and streamflow (after being adjusted for the autocorrelation in precipitation) indicate the magnitude of storage reservoirs in soils or snowpacks. They may also reflect the degree of synchrony between precipitation inputs and forest vegetation controls on water losses.

2. STUDY SITES

We examined over 600 catchment-years of daily streamflow records from 18 control catchments at 4 Long Term Ecological Research (LTER) sites in Oregon (H J Andrews), New Hampshire (Hubbard Brook), North Carolina (Coweeta), and Puerto Rico (Luquillo). Figure 1 shows the location of these four sites in the United States.

The catchments examined at all four sites are relatively small, ranging in size from 6 to 101

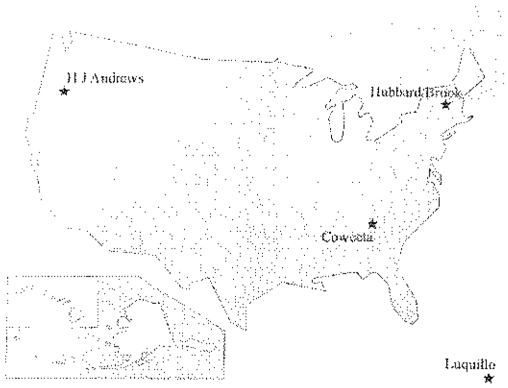

Figure 1 : Location of study sites

hectares. In addition, they are all mountainous, headwater catchments, with weir elevations ranging from 262 m to 1061 m (Table 1).

The climates of the four sites differ markedly – H J Andrews and Coweeta have very little snow and a mean annual precipitation of around 2200 mm. However, Coweeta shows more internal variability than H J Andrews, with a mean annual precipitation of 1800 mm at low elevations, and 2500 mm at higher elevations. Hubbard Brook is colder and drier than either of these two sites, with a seasonal snowpack and a mean annual precipitation of just 1300 mm. Luquillo is warmer and wetter than any of the other sites, with no snow and a mean annual precipitation of 3600 mm (Table 1).

H J Andrews has a strong winter maximum of precipitation, while Coweeta and Hubbard Brook have precipitation evenly distributed year round. Luquillo is slightly different, having a bi-modal distribution, with slight maxima in May and November. However, these maxima are not nearly as dramatic as the winter-dominated precipitation seen at H J Andrews.

Comparing vegetation, Coweeta and Hubbard Brook are the most similar, both dominated by deciduous broadleaf species. H J Andrews is dominated by evergreen needleleaf, while Luquillo is dominated by evergreen broadleaf (Table 1). These contrasts are due to Coweeta and Hubbard Brook being in the north-eastern United States, while H J Andrews is in the north-west. Luquillo, on the island of Puerto Rico has a tropical climate and vegetation (Figure 1).

The hydrologic response of all of the catchments at each site was examined in detail (Post and Jones, 1999; Jones and Post, 1999). From this examination, we chose one or two which were representative of the hydrologic response at each site. At H J Andrews, we chose AND02; at Hubbard Brook, HBR03; and at Luquillo, LUQ03. At Coweeta, a large elevation range (Table 1) produces contrasting responses between low and high elevation catchments. Consequently, CWT02 was taken to be representative of the low elevation catchments, and CWT27 was taken to be representative of the high elevation catchments. This subset of five catchments will be analysed here.

	H J Andrews	**Coweeta**	**Hubbard Brook**	**Luquillo**
Number of catchments	8	17	8	3
Catchment sizes (ha)	10 - 101	9 - 61	12 - 76	6 – 35
Weir elevations (m)	442 - 955	696 - 1061	442 - 619	262 – 270
Mean annual temperature range (°C)	1 - 19	3 - 22	-9 - 19	17 - 20
Mean annual precipitation (mm)	2200	2300	1300	3600
Snowpack	transient	rare	seasonal	none
Vegetation type	Evergreen needleleaf	Deciduous broadleaf	Deciduous broadleaf	Evergreen broadleaf
Dominant tree spp.	Douglas fir, western hemlock	Oak, pine	Beech, sugar maple, yellow birch	Tabonuco, palm
Reference	Rothacher *et al.* (1967)	Swank and Crossley (1988)	Likens *et al.* (1977)	Weaver (1994)

Table 1 : Major characteristics of the study sites

3. METHODS

To relate the streamflow response time to a precipitation input, we decomposed the temporal relationship between precipitation and runoff. Because precipitation can be autocorrelated (i.e., it has a repeating pattern over time, such as seasons, or consistent storm lengths), we fitted an autocorrelation model (Norusis, 1993) to the precipitation data:

$$P_t = a_0P_t + a_1P_{t-1} + a_2P_{t-2} + ... + a_nP_{t-n} \qquad (1)$$

where a_0 represents a correlation between precipitation in the current time period and precipitation one time period in the past, and a_n represents a correlation between precipitation in the current period and precipitation n time periods in the past.

Because runoff is correlated with precipitation in the present and past time periods, we fitted a cross-correlation model (Norusis, 1993) to precipitation and runoff data:

$$R_t = c_0P_t + c_1P_{t-1} + c_2P_{t-2} + ... + c_nP_{t-n} \qquad (2)$$

where c_0 represents a correlation between runoff and precipitation in the current period, and c_n represents a correlation between runoff in the current period and precipitation n time periods in the past. This cross-correlation between streamflow and precipitation is due in part to the autocorrelation on precipitation. To remove this effect, we defined an adjusted cross-correlation term:

$$c'_0 = a_0 - c_0 \qquad (3)$$

which is the net cross-correlation attributable to stored precipitation, minus any effect of seasonality (monthly timestep) or storm event duration (daily timestep).

4. RESULTS

4.1 Monthly Timestep

At H J Andrews, precipitation is significantly positively autocorrelated with precipitation in the subsequent two months, significantly negatively autocorrelated with precipitation four to eight months later, and positively autocorrelated again in months 10, 11, and 12. (Figure 2(a)). This pattern reflects the strong wetter-than-average winter (DJF) and drier-than-average summer (JJA) at H J Andrews. The lack of significant autocorrelations at Coweeta and Hubbard Brook (Figure 2 (b) – (d)) reflects the lack of seasonality in precipitation at those sites. At Luquillo, significant positive autocorrelations occur in months 1, 2, 5, 6, 7, 11, and 12 (Figure 2 (e)), reflecting both the slight seasonality and bi-modal distribution of precipitation.

Cross-correlations between streamflow and precipitation on a monthly timestep are also shown in Figure 2. Adjusted cross-correlations as defined in (3) are shown in Figure 3. Positive adjusted cross-correlations occur at various lags, ranging from one to five months at AND02 (Figure 3 (a)); one to four months at CWT02 (Figure 3 (b)); one to three months at CWT27 (Figure 3 (c)); four to six months at HBR03 (Figure 3 (d)); and one to three and eight to ten months at Luquillo (Figure 3 (e)).

Positive adjusted cross-correlations represent higher-than-expected runoff at a given lag relative to higher-than-average precipitation (or lower-than-expected runoff at a given lag relative to lower-than-average precipitation). Thus, the consecutive positive adjusted cross-correlations at Coweeta and H J Andrews indicate that a storage reservoir is present that is able to retain and release extra moisture (or retain and fill a soil moisture deficit) for up to three (CWT27), four (CWT02), or five (AND02) months. For HBR03, the absence of significant adjusted cross-correlations for months 1, 2, and 3, followed by positive adjusted cross-correlations for months 4, 5, and 6 (Figure 3(d)), indicates that a storage reservoir is present that is able to retain extra moisture (or retain a soil moisture deficit) for three months, and then release that moisture (or fill that deficit) in the subsequent three months. Long-term soil moisture reservoirs that vary in their capacities provide plausible explanations for the adjusted cross-correlations at Coweeta and H J Andrews, while a seasonal snowpack which fills once and then empties months later provides a plausible explanation for the adjusted cross-correlations at Hubbard Brook. The one to three month adjusted cross-correlation at Luquillo may be due to a small soil moisture reservoir, but the eight to ten month correlation appears to be an artefact of the bimodal precipitation distribution and short (10 year) period of record.

4.2 Daily Timestep

Daily precipitation was significantly autocorrelated at lags of at least 14 days at H J Andrews (Figure 4 (a)), 1 day at Coweeta and Hubbard Brook (Figure 4 (b) – (d)), and 6 days at Luquillo (Figure 4 (e)). These patterns suggest that

H J Andrews is dominated by long-lasting precipitation events, Luquillo by shorter events, while at Hubbard Brook and Coweeta, precipitation events do not typically last more than one day.

Cross-correlations between streamflow and precipitation on a daily timestep are also shown in Figure 4. Adjusted cross-correlations as defined in (3) are shown in Figure 5. Strong positive adjusted cross-correlations last at least 14 days at AND02 (Figure 5 (a)). The response at CWT02 (Figure 5 (b)) is much weaker, while that at CWT27 (Figure 5 (c)) is very strong initially but fades away quickly. The response at HBR03 (Figure 5 (d)) only lasts a few days, while that at LUQ03 (Figure 5 (e) is very weak.

Positive adjusted cross-correlations represent higher-than-expected runoff at a given lag relative to higher-than-average precipitation (or lower-than-expected runoff at a given lag relative to lower-than-average precipitation). Thus, the consecutive adjusted positive cross-correlations indicate that a storage reservoir is present that is able to retain and release extra moisture (or retain and fill a soil moisture deficit) over at least 14 days at AND02 and CWT27, and only over a few days at HBR03. CWT02 and LUQ03 seem to have only a very small soil storage capacity at a daily timestep. Short-term soil reservoirs that fill and empty over a few days but vary in their capacities provide plausible explanations for these cross-correlations. Interestingly, at AND02, CWT02, and LUQ03, the peak cross-correlation occurs at day two (Figure 5 (a), (b) and (e)), indicating that a pulse of precipitation is detained for a day and then released from the short-term soil reservoir.

5. CONCLUSIONS

This study has shown how cross-correlations between streamflow and precipitation, along with autocorrelations in precipitation, can be used to quantify the role of soil and snow storage on the hydrologic response of a catchment. The implications of this for evapotranspiration and thus the hydrologic budget of a catchment are assessed in Post and Jones (1999).

The storage of water, in both soils and snowpack, has a major but differing impact on the hydrologic response of small forested mountain catchments in Oregon (H J Andrews), North Carolina (Coweeta), New Hampshire (Hubbard Brook), and Puerto Rico (Luquillo). Understanding the role of soil and snow storage on hydrologic response allows us to make predictions of the hydrologic response of similar catchments in these regions. In order to extrapolate to catchments outside these regions (or to much larger or smaller scales), we must first determine whether the hydrologic processes that were important here are in fact important in these other regions (or at these other scales).

The dominant controls on hydrologic response must be understood before any attempt is made to transfer a prediction of hydrologic response from one region to another. Failure to do this could mean that one is transferring hydrologic mechanisms that may be important in the region where a hydrologic model was calibrated, but are of no importance in the region for which we hope to make predictions.

6. ACKNOWLEDGMENTS

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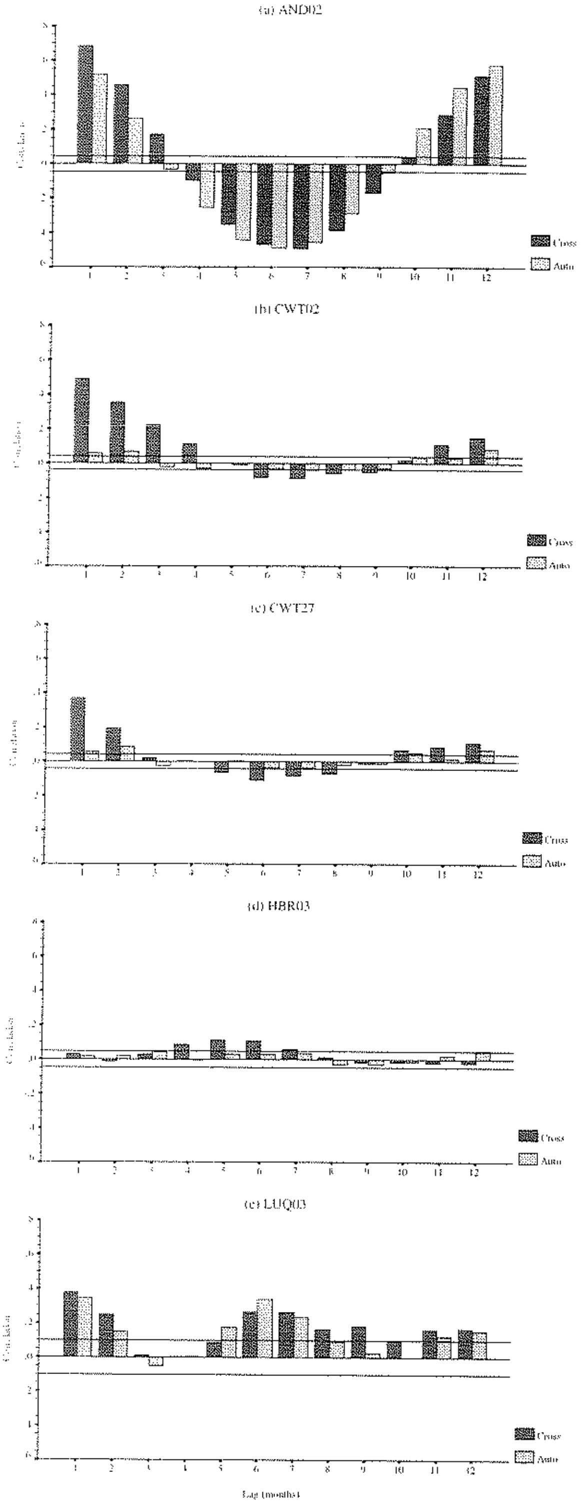

Figure 2 : Autocorrelation on precipitation and cross-correlation between precipitation and streamflow at a *monthly timestep* for (a) AND02; (b) CWT02; (c) CWT27; (d) HBR03; (e) LUQ03. Horizontal lines indicate statistical significance.

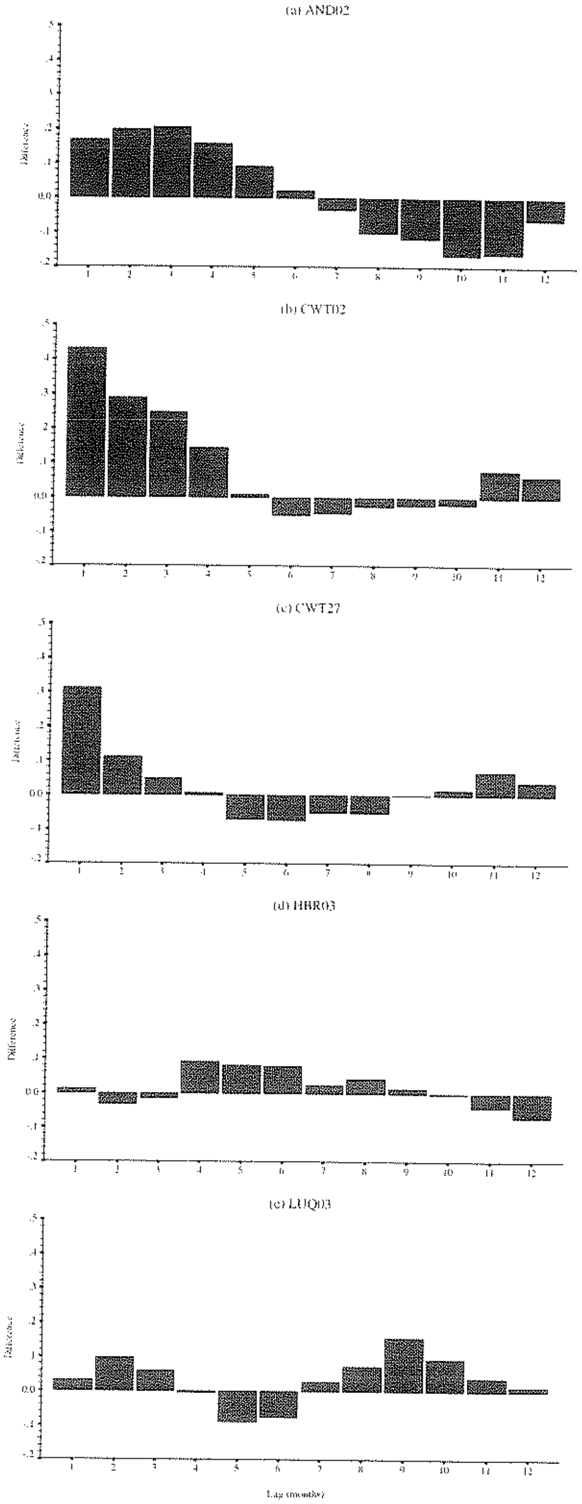

Figure 3 : Adjusted cross-correlation between precipitation and streamflow at a *monthly timestep* for (a) AND02; (b) CWT02; (c) CWT27; (d) HBR03; (e) LUQ03. Positive values indicate the magnitude and duration of the monthly catchment store.

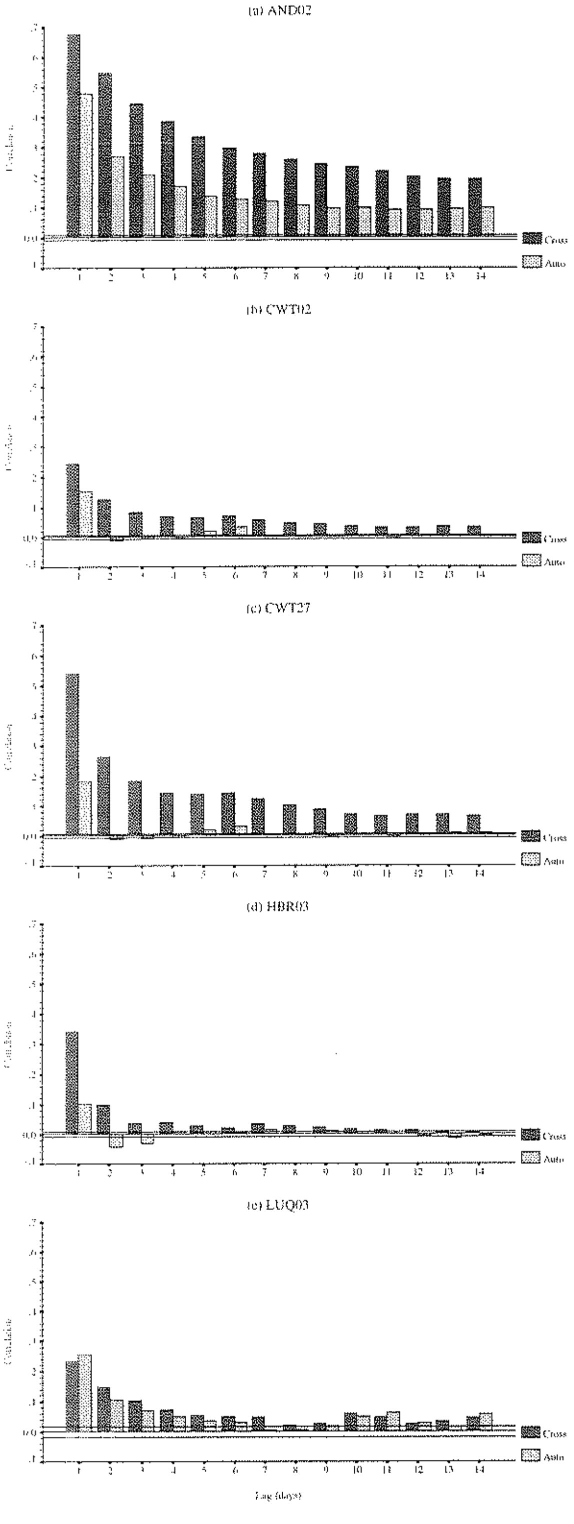

Figure 4 : Autocorrelation on precipitation and cross-correlation between precipitation and streamflow at a *daily timestep* for (a) AND02; (b) CWT02; (c) CWT27; (d) HBR03; (e) LUQ03. Horizontal lines indicate statistical significance.

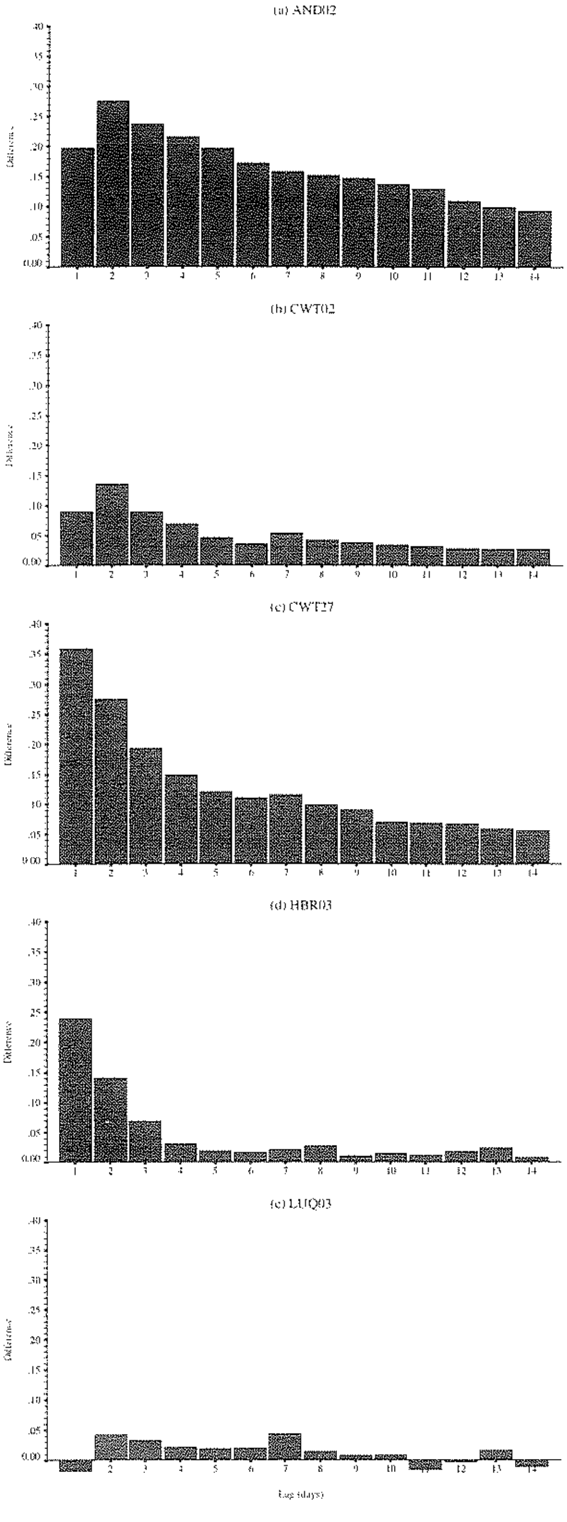

Figure 5 : Adjusted cross-correlation between precipitation and streamflow at a *daily timestep* for (a) AND02; (b) CWT02; (c) CWT27; (d) HBR03; (e) LUQ03. Positive values may be thought of as the catchment 'response time' to precipitation.