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Hydrologic inferences from comparisons among small basin experiments

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The hydrologic community is poised to make important advances in basic hydrology through comparative analysis of small basin experiments around the world. Existing long-term records from small basins have already enriched our knowledge of fundamental processes and important societal issues, and yet they contain a wealth of untapped information about hydrologic and biogeochemical responses to climate change, natural disturbance and human activities over a wide range of climate, geophysical and vegetation settings.

Background

Since near the start of the 20th century, small experimental basin studies in a wide variety of environments have contributed to basic understanding of hydrology, but their role has declined in the past several decades. Small basin studies have been criticized for having a parochial, management-oriented focus, lacking emphasis on process, and having outlived their relevance to the management treatments. New scientific tools and issues have shifted hydrologists' focus away from small basins to coarser and finer spatial scales, and from themes such as forestry impacts to environmental change themes, such as alterations of biogeochemical cycles by atmospheric deposition. Also, many of the scientists who championed the early small basin studies have retired, and many small basin experiments have been abandoned or are at risk as agency priorities shift.

Studies at a small subset of the ongoing basin experiments have grown in scope. These studies have been relevant to environmental change issues such as acid rain and nitrogen deposition, and have involved the ecology community, e.g. through the United States National Science Foundation's Long-Term Ecological (LTER) network http://www.lternet.edu and the US Geological Survey's (USGS) Water, Energy and Biogeochemical Budgets programme (http://water.usgs.gov/nrp/webb/). Although research at each intensively studied small basin site has produced many valuable insights, it has been difficult to derive general hydrologic principles because the sites represent diverse hydro-ecosystems undergoing distinctive types of environmental change at different paces. This diversity can be an asset when viewed in terms of the potential it represents

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for drawing general insights from comparative analysis (Post *et al.*, 1998).

Current developments

A renaissance is occurring among small basin studies, in response to contemporary science and policy issues, new technology and the acknowledged value of sites with strong research histories and useful temporal and geographic contexts. New data analysis techniques applied to accumulated long records (30 to over 60 years) from experimental basin studies allow inferences about hydrologic mechanisms and their geographical variation. The essence of the method is to examine the temporal behaviour of differences in streamflow at a given temporal resolution (days, storms, season, years) among two or more basins that are known to differ in one or more respects over at least part of the record. We have compared basins on the basis of different treatments, such as forest canopy removal and/or road construction (Jones and Grant, 1996; Jones, 2000), or different vegetation, hillslope residence times or snowpacks (Post *et al.*, 1998; Post and Jones, 2001; Jones and Post, in preparation, Perkins, in preparation). Findings include the following.

Small basin streamflow records embody variability across multiple time and space scales that are indicative of hydrologic process controls; these processes are revealed by statistical analyses of

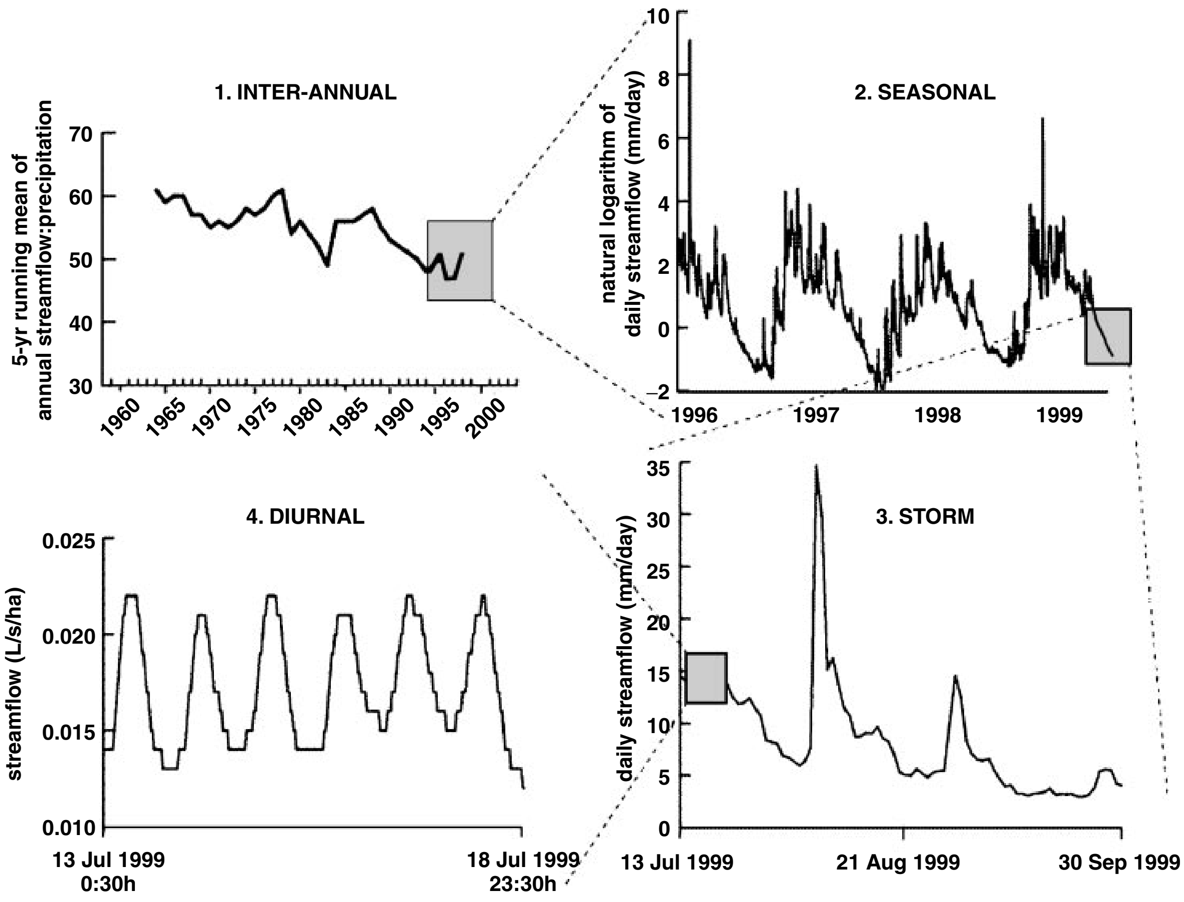

Figure 1. Conceptual model of multiple time scales at which stramflow interacts with various factors: 1, succession, climate change; 2, seasonality of climate, evapotranspiration; 3, hillslope residence times; 4, diurnal water use by vegetation, Data from Andrews LTER control basin (WSZ)

selected combinations of locations and time scales. We find that four 'natural' time scales capture potential interactions among vegetation, soil, snow and streamflow: interannual, seasonal, storm and diurnal (Figure 1). The relative amounts of variation, and the degree of coupling and lag times between precipitation and streamflow, at each of these different time scales provide a signature of each basin (Post and Jones, 2001). This signature may predict a basin's response to particular kinds of environmental changes (Jones and Post, unpublished data). When long-term records are examined at multiple sites, there is great potential for insights into hydrologic processes in small basins from autocorrelations and cross-correlations (Post and Jones, 2001), spectral analysis (e.g. Kirchner *et al.*, 2000) and cross-spectral analysis. Comparative analyses may involve multiple (treated and/or control) basins within a site (Jones and Grant, 1996), within a region (the Pacific Northwest USA, e.g. Jones, 2000), or across regions (Andrews, Coweeta, Hubbard Brook and Luquillo LTER sites, USA; Post and Jones, 2001; Jones and Post, unpublished data). Here, we draw inferences from these analyses about three hydrologic processes (and corresponding reservoirs): evapotranspiration (vegetation), moisture storage and release from hillslopes, and moisture storage and release from snowpacks.

1. Streamflow response to vegetation is greatest during periods when water use by vegetation is high relative to storages in soil and snow; these periods are revealed by comparing small basins with contrasting vegetation due to differences in biogeographic region or modification by humans. Increases in peak discharges after conifer forest canopy removal are large in relative terms, but rather small in absolute terms during the moisture-limited fall period in the Pacific Northwest (Jones and Grant, 1996; Jones, 2000). Streamflow responses to experimental forest canopy removal indicate that vegetation water use is relatively high almost year-round in conifer forests of the Pacific Northwest USA, but relatively low and seasonally limited in deciduous forests in the northeast and southeast USA. Thus, we hypothesize that vegetation water use interacts with climate so as to damp variability in the streamflow hydrograph relative to climate in some cases (e.g. conifer forest) or magnify it in other cases (e.g. deciduous forest). This hypothesis merits testing in basins with a wider range of vegetation types and amounts, across a broader range of climate.
2. Streamflow differs among basins according to the distribution of hillslope residence times, or flowpath lengths, in the basin, and streamflow responds to modification of these flowpaths, for example by road construction. Hence, road construction combined with small amounts of forest canopy removal produced similar increases in peak discharges as those from 100% forest canopy removal, during wet, winter periods (Jones and Grant, 1996). Increases attributable to hillslope flowpath modification in the northwest USA are small in relative terms, but large in absolute terms, because they occur during the winter period of large peak discharges. We hypothesize that basins most sensitive to hillslope flowpath modification are those with shallow, subsurface flowpaths; this produces contrasting responses to road construction in basins with steep hillslopes and shallow soils versus gentle slopes and deep soils. More intersite comparative work on hillslope hydrology has the potential to reveal basin characteristics that contribute to disruption of flowpaths from hillslope modifications such as road construction and reconnection of 'natural' flowpaths from e.g. road removal.
3. Streamflow response to snow reservoirs is mediated by vegetation and hillslopes, with the greatest response during periods when (or in places where) vegetation water use is low and soils have limited moisture storage capacity relative to water stored in, or melted from, snowpacks. These periods are revealed by comparisons among basins with contrasting snowpacks and hillslopes, with and without vegetation modification. Increases in rain-on-snow peak discharges after forest canopy removal are greater in basins with large snowpacks (Perkins and Jones, unpublished data). Streamflow response to forest canopy removal was large and concentrated during a very short (two-week) snowmelt period in the northeast USA where soil moisture storage capacity is low, but it was protracted

and difficult to separate from spring evapotranspiration effect in the northwest USA where soil moisture storage capacity is high (Jones, 2000; Jones and Post, unpublished data). Thus, a snowpack has the potential to amplify a basin's streamflow response to a natural climate event (as in a rain-on-snow event) or damp it (as in rain stored in snow). Further comparative studies of small basin records no doubt will reveal a wider set of interactions among the snowpack, hillslope hydrology and vegetation that amplify or damp a basin's streamflow response to natural or anthropogenic inputs (as in snowmelt release of stored atmospherically deposited N; Shanley *et al.*, 2000).

In summary, a basin's streamflow may be predicted by characterizing basin storage capacities in vegetation, soil and snow, the capacity of these reservoirs to respond to inputs and demands for water, and changes over time in the relative magnitudes of these storages. Basins with very high leaf area, such as old-growth conifer forests, may have larger, longer-lasting streamflow responses to forest canopy removal than basins with other vegetation types. Basins with deep, subsurface flowpaths may be less responsive to variability in climate and vegetation modification than those with shallow subsurface flowpaths. We expect that many further insights can be gained by extending comparative analyses across a wider range of environmental gradients and disturbance types. Moreover, analyses could be expanded to involve more in-depth examination of climate, water quality (e.g. Johnson and Jones, 2000) and biogeochemistry (Church, 1997; Kirchner *et al.*, 2000), as well as streamflow.

The future

We envision a new phase of hydrologic science, invigorated by contributions from small basin experiments. To facilitate and encourage these efforts, several organizations (LTER, US Forest Service, USGS) are developing electronic databases for hydrology and linked climate data for a subset of small basin experiments and making them available to the scientific community via data harvester systems (Baker *et al.*, 2000). Intersite and interdisciplinary efforts involving new developments in hydrology modelling, tracer and dating studies of hydrologic processes and flow paths, and basin classification employed in the context of existing and nascent small basin studies can yield great benefits for hydrological and ecological sciences.

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