FALLING AT THE FIRST HURDLE: SPATIAL PRECIPITATION VARIABILITY AND THE PROBLEM OF CLOSING CATCHMENT WATER BUDGETS IN TROPICAL MONTANE ENVIRONMENTS

Mark Mulligan[1*], K.F. Arnoud Frumau[2] and L.A. (Sampurno) Bruijnzeel[2]

[1]Environmental Monitoring and Modelling Research Group, Department of Geography, King's College London, Strand, London, WC2R 2LS, UK (mark.mulligan@kcl.ac.uk)
[2]Department of Hydrology and Geo-Environmental Sciences,Faculty of Earth and Life Sciences,Vrije Universiteit, De Boelelaan 1085,1081 HV Amsterdam, The Netherlands

Introduction

The calculation of the catchment water budget is fundamental to understanding a catchment's hydrology. Water budgets are usually calculated by measuring those fluxes that are easiest to quantify (in theory precipitation, ***P*** and streamflow, ***Q***) and using the difference between them as an estimate of the more difficult to measure evaporation term (***ET***). Other (usually unmeasured) fluxes such as catchment leakage, changes in soil water storage and other forms of precipitation input (such as snow and fog) are corrected for at best but often they are simply ignored. This approach is not particularly objective but works where precipitation inputs can be confidently predicted and where leakage (***L***) is small. In areas where precipitation and/or leakage estimates are potentially subject to significant error, closure of the budget is much more difficult. Many different combinations of ***P***, ***ET*** and ***L*** can then close the budget but all but one of these combinations will be incorrect. Tropical montane volcanic uplands represent a case in point where inputs are extremely variable as a result of wind effects on precipitation and subterranean leakage can be both high and spatially variable. These combine to make standard water budget calculations extremely error prone. Without adequate knowledge of the spatial variability of precipitation inputs we 'fall at the first hurdle' in the race to quantify catchment water budgets.

Methodology

As part of a project to assess the impacts of forest conversion to pasture on water yield in the montane tropics of Costa Rica (www.geo.vu.nl/~fiesta), an 8.6 ha upland pasture catchment in the San Gerardo headwater area near Santa Elena (10.35ºN, -84.80ºW) was monitored for spatial rainfall and fog-water inputs. Spatial modelling approaches were applied to further understand the spatial variability of these inputs. An automatic weather station (AWS) provided hourly rainfall, wind speed and wind direction data and a series of 14 ground-level rainfall totalisers were distributed throughout the catchment. These instruments were in operation for more than two years but a full year spanning the period 1 July 2003 – 30 June 2004 is analysed here. To set the context we first analyse the distribution of rainfall stations for Costa Rica at the national scale. Comparison of the locations of the 356 stations in Costa Rica used by WORLDCLIM (Hijmans et al., 2005) with 90m resolution Digital Elevation Model-derived (www.ambiotek.com/topoview) terrain indices are used to understand some of the sampling issues for precipitation at the national scale. The terrain indices used are topographic exposure to winds from the cardinal directions, elevation, slope and aspect.

Subsequently we present a series of rainfall interpolations for the San Gerardo catchment. The first of these assumes that the measured value of rainfall at the AWS can be assumed for the entire catchment (as would be the case for many hydrological studies). The second interpolation uses data from all 14 gauges, with measured rainfall at each gauge converted to potential precipitation. We then use a simple spline interpolation between the potential precipitation values (Fig. 1). Potential precipitation is the gauge-derived rainfall if the orifice were always perpendicular to incoming rainfall. It therefore depends on rainfall inclination (a function of droplet size and wind speed). Wind speed at the AWS is scaled to the height of the gauges, and modelled at each gauge location on the basis of topographic exposure of each gauge to the wind direction for that hour (Mulligan and Burke, 2006). The wind speed is combined with a drop size distribution (and terminal velocity, Arazi et al., 1997) based on the rainfall intensity for that hour in order to derive the rainfall angle and potential precipitation. These are totalised for each gauge for each month and for the whole year. The third interpolation method takes the potential precipitation pattern derived by the second method in conjunction with surface slope, aspect and vegetation cover (including isolated forest remnants) in order to calculate the surface-received rainfall based on the rainfall inclination (wind speed) derived for each cell. Wind speed is modelled according to method 2 though scaled to the height of the intercepting surface (pasture or treetops) instead of gauge height. The methods are described fully in Mulligan and Burke (2006) at www.ambiotek.com/fiesta.

Results

An analysis of the location of Costa Rica's 356 rainfall stations relative to 360 and 720 randomly chosen points in Costa Rica indicates that, in terms of topographic exposure, station locations tend to be underexposed relative to the landscape as a whole (especially in terms of exposure to winds from the NE, NW and E). Stations tend to occur at only slightly higher elevations than most of Costa Rica's territory and on slightly shallower gradients (Table 1). In addition, the spacing of the stations is significantly greater than the spatial scale of variation in rainfall for the country (www.ambiotek.com/1kmrainfall). Thus individual stations may not be representative of the conditions within the catchments in which they exist and collectively the stations are not representative of the entirety of Costa Rica's landscape, especially in terms of exposure. It is thus likely that areas with the greatest wind driven rainfall receipts are poorly represented in the national network. Even if they were better represented, the standard gauges used would not capture most of the wind-driven rain.

Property	Topex_n	Topex_ne	Topex_nw	Topex_w	Topex_sw	Topex_s	Topex_se	Topex_e	Elevation	Slope gradient
actual_stations	3.99	4.04	3.43	3.50	3.70	4.37	4.37	4.15	688.78	6.62
random_points_360	4.70	4.76	4.27	4.07	3.79	4.67	4.83	4.99	500.35	8.04
random_points_720	4.40	4.39	4.11	3.81	3.62	4.34	4.48	4.72	533.52	8.38
bias	under	**under**	**under**	under	------	------	under	**under**	higher	lower

Table 1 Non-randomness of meteorological station terrain conditions for Costa Rica

Moving to the San Gerardo analysis, using the raw AWS-measured gauge rainfall value as representative for the entire catchment gives an annual rainfall total of **4199 mm** for 2003/04. The spline interpolated potential precipitation value summed over the catchment is **6393 mm (**method 2) and Figure 1 indicates that the spatial variability even within this very small catchment is substantial. In addition, the gauge-based rainfall at the AWS is likely to be quite unrepresentative of the catchment average. The spline-interpolated potential precipitation redistributed according to the underlying intercepting surface (slope, aspect and vegetation cover) and local wind speed and direction produces a total of **7696 mm** (method 3). The most accurate and spatially reaslistic of the three estimates is likely to be that obtained with method 3 because this calculates terrain-received interpolated gauge-derived potential precipitation or single gauge-received totals. It incorporates the spatial effects of larger-scale redistribution of rainfall by wind as measured by the interpolated 14 gauges (Figure 1) and the more localised rainfall, slope, aspect and exposure effects. Much of the extra rainfall received by the catchment according to this method is actually rain travelling near-horizontally in the higher and more exposed parts and thus subject to high wind speeds (Figure 2).

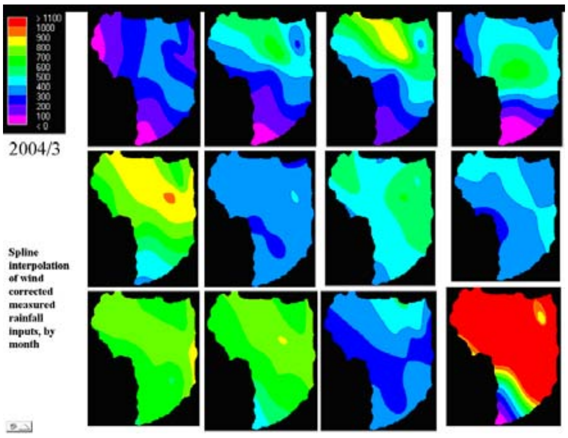

Figure 1: Monthly spatial potential precipitation based on 14 rain-gauge values for the San Gerardo pasture site (2004/3).

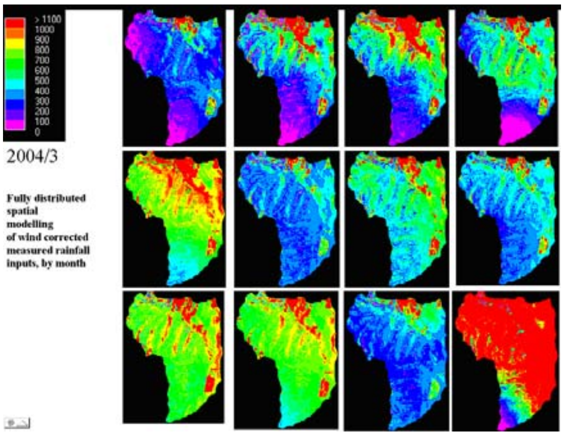

Figure 2: Monthly spatial rainfall receipts obtained from potential precipitation, surface slope, aspect and vegetation cover.

Discussion

Whilst precipitation can be more easily and accurately measured than ***ET*** at a point, it is argued here that the complexity and spatial variability of precipitation inputs in topographically complex (tropical) upland catchments is much greater than that for ***ET***. This has important implications for upland hydrological budgets since it is often assumed that measured point inputs of precipitation are close to 'truth'. The reality is that, at scales greater than the point scale, precipitation estimates are likely to be much in error for a number of reasons. These include the paucity of gauges and bias in gauge location or exposure in many upland situations, but also turbulent wind losses around the gauge (not accounted for here), wind driven rainfall inputs and inputs of other forms of precipitation which are not well measured by rain gauges (e.g. fog, also not discussed here). The spatial variability in all of these in topographically complex environments is particularly important. This is true at scales of only a few tens of hectares, let alone at the larger 'operational' scales of much hydrological enquiry. Therefore, it is argued here that water budgets in many tropical montane catchments may be significantly in error as a result of mal-estimation of precipitation inputs, even if the budgets do close. It is further argued that, in topographically variable environments, it is easier to quantify the catchment-scale ***ET*** term than the catchment-scale ***P*** term and thus more plausible water inputs may be derived on the basis of ***Q*** **+** ***ET*** = ***P*** rather than ***Q*** **=** ***P*** **-** ***ET***, so long as catchment leakage is known or negligible.

References

Arazi, A. D. Sharon, A. Khain, A. Huss and Y. Mahrer (1997) The windfield and precipitation distribution induced within a small valley. Boundary-Layer Meteorology 83: 349–374.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis (2005). Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978.

Mulligan, M. and S. Burke (2006). FIESTA: Fog Interception for the Enhancement of Streamflow in Tropical Areas. Final Technical Report for AMBIOTEK contribution to DfID FRP 7991 (downloadable from www.ambiotek.com/fiesta).

Acknowledgement

'This publication is an output from a research project funded by the United Kingdom Department for International Development (DFID) for the benefit of developing countries. The views expressed are not necessarily those of DFID. R7991 [Forestry Research Programme]'