Journal of Hydrology 462–463 (2012) 77–86

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

First-order catchment mass balance during the wet season in the Panama Canal Watershed

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ARTICLE INFO

Article history:
Available online 6 August 2010
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Throughfall
Eddy covariance
Tropical rainforest
Stemflow
Panama Canal

SUMMARY

Tropical hydrology is poorly understood for a number of reasons. Intense biological activity in the tropics introduces complexities to the hydrologic process. Bioturbation, rapid rates of decay, and intensive insect activity all tend to promote rapid flow paths in the upper soil. Aggressive weathering leads to clays depleted of light cations and deep soil profiles. Processes in the seasonal tropics are further complicated by seasonal transitions, and very large changes in catchment storage between seasons. Beginning in 2005, we installed a suite of hydrologic sensors in a 16.7 ha first-order catchment in the Panama Canal Watershed to observe hydrologic variables and identify the dominant streamflow generation processes. The site is located near the village of Gamboa, which is located on the east bank of the Panama Canal at the confluence of Lake Gatun and the Chagres River. The study catchment is located on the north side of a ridge off the eastern flank of a 230 m tall hill known as Cerro Pelado, and is covered by 70–120 year old re-growth triple-canopy forest. Measurements included: rainfall above the canopy, throughfall, stemflow, evapotranspiration, shallow groundwater levels and streamflow. Deep groundwater storage was not measured. This paper describes measurements made, data collected, and the worth of those data in estimating the mass balance closure of a first-order catchment during the wet season. We compare measurements of the different components of the water cycle with observations from other published studies from the tropics. Data analysis results indicate water balance closure errors of approximately 8%.

1. Introduction

Scientific focus on the tropics has recently become heightened as many tropical countries are undergoing rapid development and contain a vast assortment of natural resources. This growth frequently results in deforestation, a change that has attracted the attention of everyone from biologists to global climate researchers. Even with this increased scrutiny the inhospitable conditions found in many tropical locations have historically led to a disparity of detailed hydrologic studies as compared to temperate locations. Recently this has begun to change as many researchers have shifted attention to many of the unique phenomenon to be found in the tropics. A collection of literature focused on the tropics is now beginning to emerge (e.g. Bonell and Bruijnzeel, 2005; Harmon, 2005); however, much of this research is specific to individual aspects of the hydrologic cycle. Therefore, the literature provides an initial idea of specific processes that might be most important and the range of values likely to be encountered. To fully understand runoff production there are many potential pieces that are site specific and must be brought together for careful analysis.

Precipitation in any forest should be considered as both the flux of water above the canopy and that actually reaching the ground surface. Any rainfall reaching the ground surface, not intercepted by the canopy, is typically referred to as throughfall. The increased density and spatial variability of a tropical canopy complicates accurate quantification of throughfall. There have been several studies that measured throughfall in the tropics. The reported values are certainly important and represent a range likely to be found in the tropics. Throughfall remains an essential measurement for fieldwork that has been shown to be highly site dependent. Tropical site specific values in the literature range from around 50% to 92% (e.g. Wilcke et al., 2001; Scatena, 1990; Lloyd and Marques, 1988; Urbarana, 1996; Bruijnzeel, 2005). Many different techniques have been proposed to obtain site representative throughfall values. In Brazil, Lloyd et al. (1988) installed 14 rain gages along a 100 m transect that was relocated every week to reduce throughfall variability. They also augmented this transect with several more accumulating rain gages located throughout the study area. Separate studies by Moličová et al. (1997), Lloyd

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doi:10.1016/j.jhydrol.2010.07.044

and Marques (1988), Shuttleworth (1988), and Holwerda et al. (2006) also used similar setups to estimate throughfall and discussed some of the difficulties associated with the spatial variability in throughfall. Loescher et al. (2002) sought to identify the sources of error and variability that Lloyd reported by utilizing geo-statistical analyses. One important conclusion they found was that large trees and gaps in canopy cover are likely responsible for much of the spatial variability. Several of the difficulties mentioned above can be overcome by utilizing troughs with collection areas that easily surpass many standard gages combined. Large sheets of plastic that direct throughfall into a collection device have also been used with some success (e.g. Golley et al., 1975).

The amount of water that reaches the ground surface can also be enhanced by stemflow. Due to branch inclination some intercepted water from the leaf canopy drips toward the center stem or trunk of the tree increasing the amount of water to reach the ground surface. This extra source of water cannot be accounted for with throughfall collection systems. Even though it is difficult in practice to get an exact value of the amount of stemflow present due to the variability in plant species and sizes, an estimate of the relative importance can easily be obtained. Using the literature as a guide the percentage of rainfall seen as stemflow typically ranges between 0% and 4% (e.g. Lloyd and Marques, 1988; Hölscher et al., 2004; Cavelier et al., 1997; Holwerda et al., 2006), although Fournier (1978) reported a range of 1–18% globally. Herwitz (1986) found in Australia that the concentration of stemflow at the base of a tree could produce localized overland flow extending up to 10 m downslope.

Accurate estimates of evapotranspiration (ET) have proved difficult in any geographical location. Reliable data from tropical rainforests are extremely important as ET represents a significant portion of the water balance. Micrometeorological methods to directly measure ET are becoming widespread in research. However, there are very few studies in tropical forests due to the difficulty in installing the necessary instrumentation above the canopy. For a comprehensive review of such research efforts specific to the tropics the reader is referred to Roberts et al. (2005). Water budget approaches to estimating ET in tropical locations are popular because meteorological data to apply to traditional methods are often not available. Schellekens et al. (2000) point out the potentially large errors associated with estimating ET by taking the residual of a catchment water budget. They note differing studies in close proximity that have produced contradictory estimates of ET through the assumption of a "water-tight" catchment scale water budget.

The purpose of this paper is to describe hydrologic observations used in a field study designed to identify likely streamflow generation mechanisms and seasonal transitions in a first-order tropical catchment. Similar field instrumentation approaches to quantifying seasonal transitions and catchment properties have been used with success in the tropics (e.g. Tomasella et al., 2008; Hooijer, 2005). Instrumentation was installed early in the 2005 wet season to quantify of the amounts of throughfall, precipitation, evapotranspiration, and streamflow, as well as observations of stemflow. Results are considered in the context of other tropical studies. Thoughtful evaluation of mass balance results were used to assess the value of the data for future hydrologic studies. Observations of the frequency and magnitude of runoff provide some insight into the dominant runoff generation mechanisms.

2. Site description

Gamboa is a village located at the confluence of the Rio Chagres with Lake Gatun. While attempting to construct a sea-level canal the French fought many battles against the flashy Rio Chagres at this location (McCullough, 1977). Historically, Gamboa has been the home of the Panama Canal dredging division. Adjacent to Gamboa is a hill named Cerro Pelado which translates to "Bald Hill" in English. Cerro Pelado was chosen as the small-scale research site for detailed field studies due to the relative ease of access and the nearby Smithsonian Tropical Research Institute (STRI) laboratory facilities. Cerro Pelado is quite steep, abruptly rising from 30 m to a peak of 223 m above sea-level as shown in Fig. 1. It is believed that during early canal construction Cerro Pelado was clear-cut. However, a map from the mid-19th century gives the name Cerro Pelado. The vegetation can now be considered old re-growth. According to Ibáñez et al. (2002) there is little old growth forest to be found in the canal corridor due to human activity that greatly accelerated after 1870. Personal communications with STRI researchers have led to a general consensus the re-growth is probably somewhere between 90 and 120 years old. Trees average 25 m height, with several trees reaching 35 m. Deciduous trees are most prevalent in the upper canopy. Palms and younger deciduous trees form the secondary canopy layer. Smaller palm trees and undergrowth of a few meters are seen in varying degrees, resulting in triple-layer canopy in most locations.

The geology of Panama was dictated by volcanism, faulting, and erosion with the deepest and oldest rock formations typical of marine island arcs (Stallard, 2010). According to Stallard the study area is encompassed by the Gatuncillo Formation that is composed of basal conglomerates, mudstones, siltstones, some limestones, and an upper algal limestone 14–50 m thick. There are several outcrops that reveal that the bedrock is heavily fractured. Along the hillslope transect there is a 5.5 m bedrock cliff that is cross-cut by several 5 cm fractures. As such, the soils are Ferralsols, with a pronounced decrease in infiltrability as measured by a tension infiltrometer at a depth from 20 to 50 cm, which is approximately the bottom of the bioturbation layer.

A detailed climate record exists at Gamboa because of canal operations with rainfall records dating back as far as 1897. In Panama the rainy season generally persists from May until December and the dry season from mid- to late- December until April. Gamboa is located roughly in the middle of the Panamanian isthmus, and typically receives less than 20 mm of rainfall during the

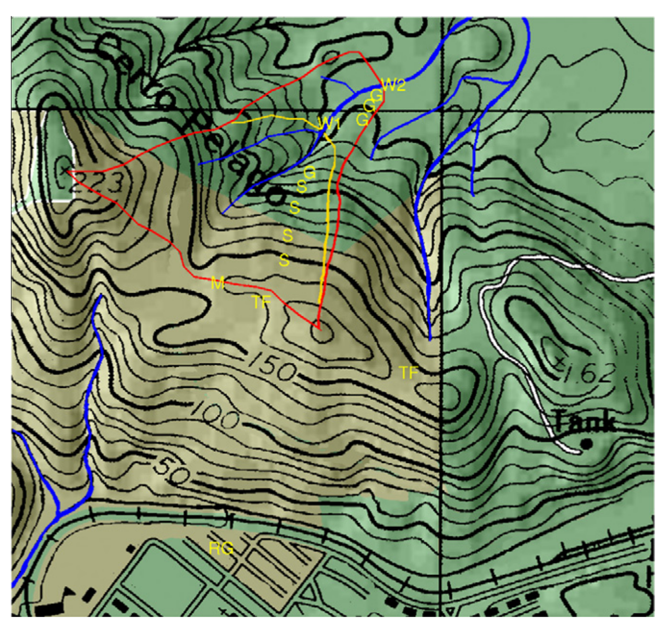

Fig. 1. Contour map of the Cerro Pelado study area. Annotations on the contour map represent the following monitoring locations: 'M' for the ET tower, 'S' for soil moisture, 'TF' for throughfall and stemflow locations, 'G' for shallow groundwater wells, and 'W' for weir locations.