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Requirements for throughfall monitoring: The roles of temporal scale and canopy complexity

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ABSTRACT

A wide range of basic and applied problems in water resources research requires high-quality estimates of the spatial mean of throughfall. Many throughfall sampling schemes, however, are not optimally adapted to the system under study. The application of inappropriate sampling schemes may partly reflect the lack of generally applicable guidelines on throughfall sampling strategies. In this study we conducted virtual sampling experiments using simulated fields which are based on empirical throughfall data from three structurally distinct forests (a 12-year old teak plantation, a 5-year old young secondary forest, and a 130-year old secondary forest). In the virtual sampling experiments we assessed the relative error of mean throughfall estimates for 38 different throughfall sampling schemes comprising a variety of funnel- and trough-type collectors and a large range of sample sizes. Moreover, we tested the performance of each scheme for both event-based and accumulated throughfall data. The key findings of our study are threefold. First, as errors of mean throughfall estimates vary as a function of throughfall depth, the decision on which temporal scale (i.e. event-based versus accumulated data) to sample strongly influences the required sampling effort. Second, given a chosen temporal scale throughfall estimates can vary considerably as a function of canopy complexity. Accordingly, throughfall sampling in simply structured forests requires a comparatively modest effort, whereas heterogeneous forests can be extreme in terms of sampling requirements, particularly if the focus is on reliable data of small events. Third, the efficiency of trough-type collectors depends on the spatial structure of throughfall. Strong, long-ranging throughfall patterns decrease the efficiency of troughs substantially. Based on the results of our virtual sampling experiments, which we evaluated by applying two contrasting sampling approaches simultaneously, we derive readily applicable guidelines for throughfall monitoring.

1. Introduction

Accurate and precise estimates of throughfall are required for a variety of applications in meteorology, hydrology, ecology, and biogeochemistry. One such application is interception modeling which enables the prediction of interception loss. These models require specification of parameters such as the canopy storage capacity and the free throughfall coefficient (Muzylo et al., 2009), which are usually derived from regressions of throughfall on rainfall (e.g. Gash and Morton, 1978; Herbst et al., 2008; Jackson, 1975; Leyton et al., 1967; Lloyd et al., 1988; Schellekens et al., 1999). Not surprisingly, the quality of throughfall data strongly influences the accuracy of these parameter estimates and hence, the performance of interception models (Hutjes et al., 1990; Lloyd et al., 1988). Given the large within-stand variation of throughfall and the resulting difficulties with sampling, Vrugt et al. (2003) supposed that throughfall measurements contain insufficient information for parameter derivation. The same authors therefore suggested calculating the canopy water storage from the attenuation of microwave signals. Linking microwave attenuation to actual water storage, however, requires a careful calibration on throughfall data (Bouten and Bosveld, 1991; Bouten et al., 1991; Calder, 1991). In other words, there is no escape from the ugly truth: precise and accurate throughfall estimates are mandatory regardless of the method applied to derive the canopy storage parameters for interception modeling.

Other applications requiring throughfall data involve assessments of land cover changes on local water fluxes (Dietz et al., 2006; Holwerda et al., 2010; Macinnis-Ng et al., 2012; Ponette-González et al., 2010; Schrumpf et al., 2011), studies of the influence of forest structure on rainfall partitioning (Brauman et al., 2010; Krämer and Hölscher, 2009), or comparisons of solute fluxes in different forest ecosystems (Dezzeo and Chacón, 2006; Hofhansl et al., 2011; Macinnis-Ng et al., 2012). All these investigations

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also critically depend on the quality of throughfall data because they often attempt to detect comparatively minor, yet important, differences in rainfall partitioning among forests.

Given these quality requirements, one could assume that throughfall sampling strategies are constantly optimized. A literature survey (Supplementary material S1), however, reveals that sampling efforts changed little throughout the past four decades, and applied sample sizes are constantly small (e.g. the median sample size of applied funnel-type collectors was 20 in the years 1970–1999 and did not change thereafter; Supplementary material S1). Hence, evidence seems to be ignored that many sampling schemes may not be well adapted to the heterogeneity of the studied forest (Holwerda et al., 2006; Kimmins, 1973; Zimmermann et al., 2010). Apart from logistical and financial constraints, the mismatch between theoretically required and practically applied sampling routines is due to the scarcity of general guidelines that would help adapting throughfall sampling schemes to the forest system under study. Although a variety of studies calculated sample sizes to reach pre-specified error limits (Kimmins, 1973; Rodrigo and Àvila, 2001; Price and Carlyle-Moses, 2003; Puckett, 1991; Seiler and Matzner, 1995), compared the performance of different collector types (Cuartas et al., 2007; Kostelnik et al., 1989), or assessed the results of roving versus fixed sampling schemes (Holwerda et al., 2006; Ritter and Regalado, 2010; Ziegler et al., 2009), it is difficult to derive general guidelines from these studies as most of their findings are only valid for the tested collector types and sampling designs (Holwerda et al., 2006). In practice, however, one has to decide on the entire sampling scheme including collector type (trough versus funnel), sampling design (simple random sampling versus other random sampling designs), and sample size. Interestingly, the German Association for Water, Wastewater and Waste (DWA, formerly DVWK) published guidelines for interception monitoring (DVWK, 1986), and similar manuals are available in other countries as well (e.g. Clarke et al., 2010; McJannet and Wallace, 2006; Žlindra et al., 2011). Yet, most of these technical reports focus on practical issues, such as optimizing the construction of throughfall collectors, but do not consider aspects of sampling theory.

A possible way forward is to conduct virtual sampling experiments based on stochastic simulations of realistic throughfall fields (Zimmermann et al., 2010). These experiments, which have been already used in other disciplines such as soil science (Papritz and Webster, 1995), permit to derive more generally applicable findings. In a previous study, Zimmermann et al. (2010) tested various throughfall sampling designs (e.g. simple random sampling versus cluster random sampling) and sample supports (e.g. trough versus funnel-type collectors) in respect of their suitability to estimate mean throughfall in an old-growth tropical forest and derived two main findings. First, sampling designs that avoid a strong clustering of sampling locations, such as simple random sampling or stratified simple random sampling are to be preferred, particularly in the presence of pronounced spatial dependence. Second, troughs are usually more efficient than funnel-type samplers. However, Zimmermann et al. (2010) suggested that the efficiency of trough systems may deteriorate in the presence of pronounced spatial structures in throughfall, but their data base (one forest type and 14 rainfall events) was too small for a complete picture. This work builds upon the findings of Zimmermann et al. (2010).

2. Objectives and outline of the article

The main objective of this study is to test the performance of sampling schemes for the estimation of mean throughfall. More precisely, we address the following research questions. (1) How do event size and temporal aggregation of throughfall data influence the accuracy of mean throughfall estimates? (2) Given a certain aggregation level, is there an influence of canopy complexity on throughfall variability, which involves the need to adapt sampling strategies to the ecosystem under study? (3) How do temporal aggregation and canopy complexity influence the characteristics of throughfall spatial correlations and hence, the efficiency of trough-type sampling systems? The tested sampling schemes involve a variety of funnel-type and trough-type collectors and a wide range of sample sizes. Our calculations are based on the virtual sampling of simulated throughfall fields which we generated using real-world data from three forest stands of contrasting canopy complexity. To check the plausibility of the simulation results, we also applied two contrasting sampling approaches at one of the study sites simultaneously.

The article is arranged as follows. First, we briefly describe the study sites and the sampling of the real-world throughfall data. Second, we explain the generation of simulated throughfall fields and the virtual sampling experiments. Third, we characterize the throughfall data which is used for the virtual sampling. Fourth, we describe the performance of the tested sampling schemes. Fifth, we check the plausibility of the results obtained by the virtual sampling experiments. Finally, we discuss how the findings of this study can provide guidance for future throughfall and interception studies.

3. Methods

3.1. General description of the research area

We measured throughfall in three square 1-ha plots which span a gradient of forest diversity and complexity. Additionally, we measured rainfall in a distance of around 50 m to the throughfall plots. All sites are located in the central part of the Panama Canal Watershed (Fig. 1). The natural vegetation of the area is classified as semideciduous lowland forest (Foster and Brokaw, 1996). At present, the central part of the Panama Canal Watershed comprises several land use types including mature and secondary forest, cattle pastures and other farmland (Fig. 1). Protected old-growth forests cover large areas along the banks of the canal as well as the islands in the Lake Gatun. The climate of central Panama is tropical with distinct wet and dry seasons. The wet season lasts approximately from May to December. According to long-term records from Barro Colorado Island (Fig. 1), annual rainfall averages 2641 ± 485 mm (mean ± 1 standard deviation, $n = 82$, data from 1929 to 2010, courtesy of the Environmental Sciences Program, Smithsonian Tropical Research Institute, Republic of Panama). Mean daily temperature, measured at the latter site, varies little throughout the year and averages 27 °C (Dietrich et al., 1996).

3.2. Description of the study plots

Plot 1 (Fig. 1) is a 12-year old teak (*Tectona grandis*) plantation located in flat terrain near the village Las Pavas. The stand structure in this plot is uniform: trees are planted in regular rows of 3 m distance, there is only little understory, and stand height is even and approaches approximately 10 m. The sparse understory in plot 1 consists of a few palms (*Oenocarpus mapora*) and some pioneer trees (*Cecropia insignis*).

Plot 2 (Fig. 1) is a 5-year old secondary forest located on a 20° slope in the Agua Salud Project area (Hassler et al., 2011). Its stand structure is non-uniform with dense vegetation in some parts of the plot and very open spots in others. Tree height in this stand varies between 2 m and 6 m. According to a botanical survey accompanying the throughfall monitoring, plot 2 contains 72 tree species