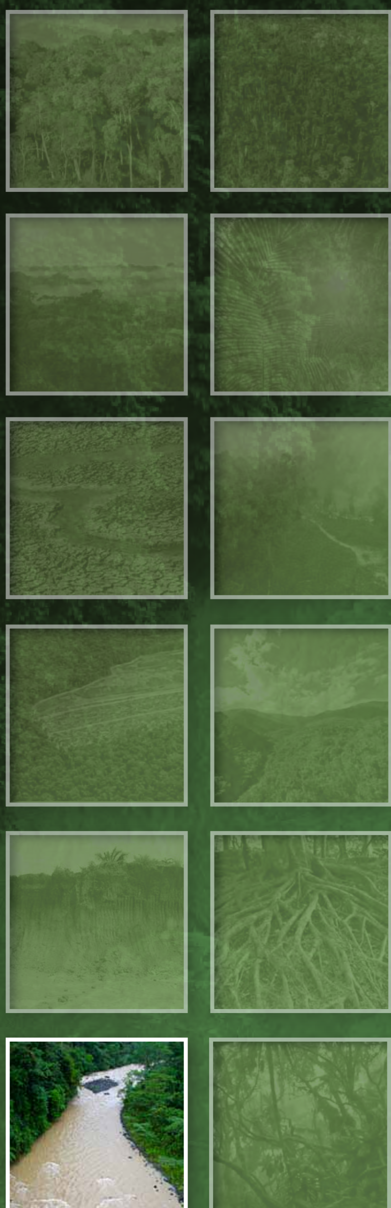

CHAPTER 11

Hydrology Within Tropical Natural Forests: Implications for Large-Scale Ecosystem Modeling

Hydrology Within Tropical Natural Forests: Implications for Large-Scale Ecosystem Modeling

The discipline of hydrology when focused on issues pertinent to tropical natural forests (sometimes described as "tropical forest hydrology"; Bonell 1999) may be divided into the study of (1) canopy hydrology and (2) hydrologic or "runoff" pathways (Bonell 2004; Wohl et al. 2012).

Canopy Hydrology: Water Interactions Among the Atmosphere, Forest Canopy, and Land

Two central concerns for studying canopy hydrology within forests are (1) the effect of the vegetation canopy on the magnitude and distribution of rainfall reaching the ground surface and (2) the flux of water to the atmosphere by evapotranspiration mechanisms, also described as "latent heat flux" or simply "evaporation" (Penman and Schofield 1951).

Rainfall received by the canopy of a tropical natural forest is a fundamental component of the regional (and global) water cycle and is the key driver for:

- The rate of wet-canopy evaporation (a component of evapotranspiration).
- Rates and location of water flows on and below the ground surface.
- Rates of nutrient and carbon mobilization and transport within watersheds.
- River behavior (including nutrient and carbon losses).

When compared to temperate biomes, the higher rainfall intensities characteristic of tropical forests can have a disproportionate effect (due to nonlinearities in the hydrological system) on the dynamics of wet-canopy evaporation (Calder 1996) and the preferential pathways of water, nutrients, and particles (mineral or organic) toward tropical rivers (Chappell 2010; Walsh et al. 2011; Zimmermann, Francke, and Elsenbeer 2012). This is particularly the case in natural forest areas beneath tropical cyclone tracks—including the Caribbean, Queensland (Australia), Madagascar, and the Philippines—given their even greater rainfall intensities (Bonell, Callaghan, and Connor 2004; Howard et al. 2010; Chappell et al. 2012). Because of the impact of these regional differences in rainfall characteristics, large-scale ecosystem models must be able to capture how nonlinearities affect the hydrologic pathways and associated subsurface nutrient and carbon flows within small, low-order watersheds that contribute most riverflow and hence aquatic (chemical and particulate) flux within tropical natural forests.

Evapotranspiration is the summation of flux by wet-canopy evaporation (sometimes ambiguously called "interception loss"), transpiration, soil evaporation, and open-water evaporation. Recent advances in the direct measurement of evapotranspiration over subminute to interannual timescales using the eddy covariance (EC) method give observations over areas up to a few square kilometers that can assist parameterization and evaluation of regional or global ecosystem models (Mueller et al. 2011). Synchronous measurement of latent heat, sensible heat, and carbon dioxide (CO_2) fluxes with EC systems allows study of the interactions among key variables of the global water and carbon budgets. This is an essential aspect of intrinsically interdisciplinary ecosystem models, such as Community Land Model (CLM) 4.0 (Barron-Gafford et al. 2012). Though the number of tower-based EC systems is increasing within tropical natural forests, (Fisher et al. 2009), it is only a fraction of the number of published studies on basin water balance across this biome (Bruijnzeel 1990).

A key uncertainty arising from the extensive basin studies within forested and adjacent land uses—whether in the Humid Tropics or across all global biomes—is the large variability in change to evapotranspiration with forest cutting or establishment. With the same proportion of forest being cut, observed evapotranspiration changes lie within a huge range of values, whether expressed as a depth of evaporation (mm) or a proportion of rainfall (Andréssian 2004; Brown et al. 2005).

This variability makes it difficult to generalize how regional evapotranspiration is affected by various intensities of tropical natural forest cutting. The Zhang et al. (2001) generalization (so-called "Zhang curves") is based on 250 global studies, including 35 basin studies from tropical latitudes. It indicates that forests have significantly higher evaporation rates compared to grasslands where annual precipitation is high (>2000 mm per year), but the rates are comparable in low rainfall areas (<500 mm per year). Important to note is that some of the variability in the evapotranspiration difference between forests and herbaceous vegetation arises from errors in basin water-balance studies. Many studies use basins that are too small (<0.5 km^2) to discount the effects of deep seepage (so called "basin leakage"), resulting in overestimation of evapotranspiration totals from annual rainfall minus river discharge balances (Bruijnzeel 1996). In addition, many reforestation studies are not monitored long enough to show peak (or average) water-use effects (Vertessy, Zhang, and Dawes 2003), and studies monitoring the effects of forest cutting for only a few years emphasize maximum rather than longer-term differences between forests and herbaceous vegetation (Kuczera 1987; Andréssian 2004).

Earlier general circulation model (GCM) studies indicated that severe droughts within the Amazon produced by anthropogenically forced climate change could so deplete the subsurface moisture available to tropical natural forests that extensive tree mortality could occur (Cox et al. 2004). More recent studies, however, have demonstrated that Amazonian rainforests can maintain high transpiration rates during severe droughts, a finding that suggests tree roots are much deeper than specified in earlier GCM simulations (Canadell et al. 1996; Fisher et al. 2007). This in turn indicates that the subsurface moisture stores (accessible to deep tap roots) are often much deeper than the few meters specified in many GCM simulations. Consequently, an understanding of the subsurface hydrology and associated hydrologic pathways is fundamental for accurately simulating moisture availability in the dry season to support transpiration and associated tree hydraulic functions.

Hydrologic Pathways: Regulating Moisture Availability and Nutrient-Carbon Migration

The hydrologic (or water) pathways within watersheds of tropical natural forests can be defined the most unambiguously as the lateral flow routes toward a stream or river. These routes comprise:

- Lateral flow on slopes by infiltration- or saturation-excess overland flow mechanisms, both including lateral flow within the litter layer (Hewlett 1982).
- Lateral flow within the solum (i.e., A and B soil horizons).
- Lateral flow within deep saprolite (sometimes called the C soil horizon including, for example, deep granite saprolite).
- Lateral flow within rock aquifers (or localized rock fractures).

All of these terms have precise definitions within the discipline of scientific hydrology (Kirkby 1978), and much ambiguity and misinterpretation arise when used incorrectly.

The magnitude of water flow within these paths and the moisture states along them (e.g., soil moisture content, soil-water potential, and water-table depth) govern (1) the availability of moisture for consumptive use by trees within the rooting zone (including deep tap roots), (2) rates of soil organic matter decomposition, (3) rates of nutrient release and transformation, (4) weathering rates, and (5) transport of nutrients and carbon from the land system to rivers and oceans (Anderson and Spencer 1991; Proctor 2004; Buss et al. 2010; Shanley, McDowell, and Stallard 2011; Eaton et al. 2012). All these hydrologically mediated processes will need to be simulated within the next generation of regional (or global) ecosystem models.

Observations of the difference between mean annual rates of rainfall and evapotranspiration are insufficient to judge the accuracy and role of hydrologic (and hence associated nutrient) pathways represented within regional ecosystem models. Observations of the flows in each of the four lateral pathways (where present locally) through sequences of storm-events

are needed for robust validation. While infiltration- and saturation-excess overland flows can be directly measured relatively easily (at least at very small, subhectare scales), quantifying the proportion of infiltrated water that travels laterally within the solum, saprolite, and rock aquifer is extremely difficult to do without introducing artificial and very unrealistic boundary conditions (Knapp 1970; McDonnell 2003).

Particulate, carbon, nitrogen, and phosphorus fluxes within both overland or subsurface flows and then small, low-order streams of tropical natural forests are equally dynamic through individual storm events, though they are imperfectly correlated with water flow (Wilcke et al. 2009; Walsh et al. 2011). This is partly because of the highly dynamic nature of water flows within shallow hydrologic pathways (over subhourly time intervals). Flux associated with particulate transport is particularly episodic, being dominated by extreme (rare) storm events (Douglas et al. 1999). Thus, ecosystem model simulations of observed time series of nutrients and aquatic carbon must be based on very high frequency sampling (often subhourly) of concentration and flow within the low-order tropical watersheds where most of the load is sourced. Although there are significantly fewer river gauging stations within tropical forests compared to temperate biomes, those with frequently sampled water-quality data are extremely sparse. Hence, observed evidence of linkages between locally dominant hydrologic pathways and resultant physicochemical flux (even integrated at the small watershed scale via stream-based observations) is very limited within tropical forest systems (Wohl et al. 2012).

In terms of observational knowledge of the hydrologic pathways across tropical natural forests, detailed hillslope and microbasin studies have been conducted throughout the region and summarized within several publications, notably Bonell et al. (2004). However, there is no real consensus on how the presence of particular pathways can be identified at large scales relevant to global climate models or on their volumetric significance when present. This is partly because few studies have been conducted within the Tropics and the volumetric significance of each pathway at specific sites in any climatic region is debated (McDonnell 2003). Some conclusions, however, can be drawn from available experimental evidence.

Widely believed outside the tropical hydrological community is that infiltration-excess overland flow—also called Hortonian overland flow (HOF)—generates a significant proportion of flow within rivers. HOF is defined precisely as surface flow (including flow in the litter layer) generated outside channels and produced by rainfall intensities (in units of mm per hour) greater than the saturated hydraulic conductivity of the ground surface (also in mm per hour). Contrary to popular view, experimental studies show that, except for a few isolated examples (e.g., Zimmermann et al. 2012), HOF per unit basin area is only a few percent of the riverflow per unit basin area (Norcliff, Thornes, and Waylen 1979; Chappell et al. 2006). The popular misconception partly arises from misinterpreting the results of inclined-line, hydrograph separation into "stormflow" or "quickflow" and "baseflow" (or "delayed flow"; Hewlett and Hibbert 1967). This method is very useful in deriving a single number (i.e., quickflow percent) that characterizes the flashiness of a river's response (Hewlett 1982). However, this proportion should not be used to infer the percentage of the total hydrograph sourced from a particular hydrologic pathway (e.g., overland flow), as was originally envisaged by Robert Horton (Beven 1991, 2012). When such inferences are made, the volumetric importance of the (infiltration- or saturation-excess) overland flow pathway is grossly exaggerated. For example, quickflow is approximately 46% of the total hydrograph in the Danum basins within tropical natural forests in Borneo (Bidin and Greer 1997), but measured overland flow is only 4% of the total hydrograph (Chappell et al. 2006). The volumetric insignificance of this pathway does not mean that its role in transporting particulates (erosion) or nutrients from the organic surface horizons of tropical soils is unimportant. In fact, this small volume of water does much work redistributing particles (and organic solutes) across slopes to streams. Certain soil types found within the Humid Tropics typically have a lower ground-surface saturated hydraulic conductivity, K_s, (also called infiltration capacity), notably Gleysols and Vertisols (Chappell and Ternan 1992; Bonell et al. 2010). Consequently, these soils should have a greater propensity for generating overland flow (whether by HOF or saturation overland flow). However, studies

that quantify ground-surface K_s, overland flow per unit area, and riverflow per unit area are largely absent within the Humid Tropics.

With forest disturbance, soils can be affected by localized compaction from vehicles or by trampling from domesticated animals, causing ground-surface K_s to decrease locally (Bonell et al. 2010) and recover relatively slowly (Hassler et al. 2011). Within landscapes that remain forested, however, marked K_s reductions are highly localized and any HOF generated often reinfiltrates as it moves to less disturbed soils before reaching a river, an often unappreciated effect called the runoff–runon phenomenon (Bonell and Williams 1986). Even with better data on the proportion of rainfall generating HOF, an open question remains about how that process should be represented within finite element meshes of ecosystem models in which element size is so large (i.e., several square kilometers or larger) that overland flow cannot be separated from channel flow.

Given that almost all rainfall penetrating a tropical forest canopy infiltrates the ground, research into hydrologic pathways should be focused on subsurface pathways. Most streamflow-generation studies conducted within tropical natural forests have focused on examining the subsurface A and B soil horizons. However, few studies have been conducted on the role of deeper strata, notably saprolite and rock aquifers (Bonell et al. 2004). Underlying small experimental watersheds in, for example, northern Thailand (Kog Ma), Peninsular Malaysia (Bukit Tarek), Cambodia (O Toek Loork), and the central Amazon (Reserva Ducke) are many meters of deep saprolite (C soil horizon) with high saturated hydraulic conductivity. As a result, the lateral flow deep within the saprolite becomes a dominant pathway, subsequently damping the riverflow hydrograph (i.e., hydrograph recessions extending several days after a storm event; Lesack 1993). There are even fewer small experimental watersheds established on rock aquifers within tropical natural forests. Large areas of the central Amazon and Congo basins, however, are underlain by major rock aquifers (Struckmeier and Richts 2006; www.whymap.org). Where percolation readily penetrates both the solum and saprolite to recharge deep rock aquifers ("deep groundwater"), then river hydrograph recessions extending over several months clearly demonstrate the dominance of lateral flow within rock aquifers (Ockenden and Chappell 2011). Capturing in new ecosystem models the subsurface strata having root-available moisture storage and the transport of dissolved nutrients or carbon (e.g., dissolved organic carbon and CO_2) within tropical natural forests will require identifying the presence and role of deep saprolite and rock aquifers at a pantropical scale; where present, hydraulic properties also will need to be characterized. Initially, this would serve as a basis for classifying tropical hydrologic systems into those with a deep rock aquifer (Type IV), a deep saprolite (Type III), a solum developed on impermeable bedrock and limited saprolite (Type II), and steep mountains only supporting an A soil horizon (Type I). Areas observed to be dominated by HOF (where infiltration is severally restricted) might be classified as shallow Type I systems also. In very simplistic terms, Type I to IV systems might be seen to have active hydrologic depths of 0.2 m, 2 m, 20 m, and 200 m, respectively, with corresponding hydrograph time constants. Such constants are based on the recession characteristics associated with the dominant hydrologic pathways (Box, Jenkins, and Reinsel 2008) of minutes, hours, days, and months, respectively (see Fig. 11.1, p. 82; Chappell et al. 2007).

Although this conceptual model exists, it does require pantropical mapping using a combination of existing soil and hydrogeological map data combined with hydrograph recession analyses (Peña-Arancibia et al. 2010), plus further evaluation against observations from experimental basins in the Humid Tropics (Bonell et al. 2004). Such work potentially would provide the necessary pantropical parameterization for next-generation ecosystem models that would simulate (1) locations where deep rooting in deeper subsurface hydrologic systems affect transpiration and resilience against tree mortality (Fisher et al. 2007) and (2) locations where deep hydrologic pathways regulate the biogeochemistry of tropical natural forests (Buss et al. 2010).

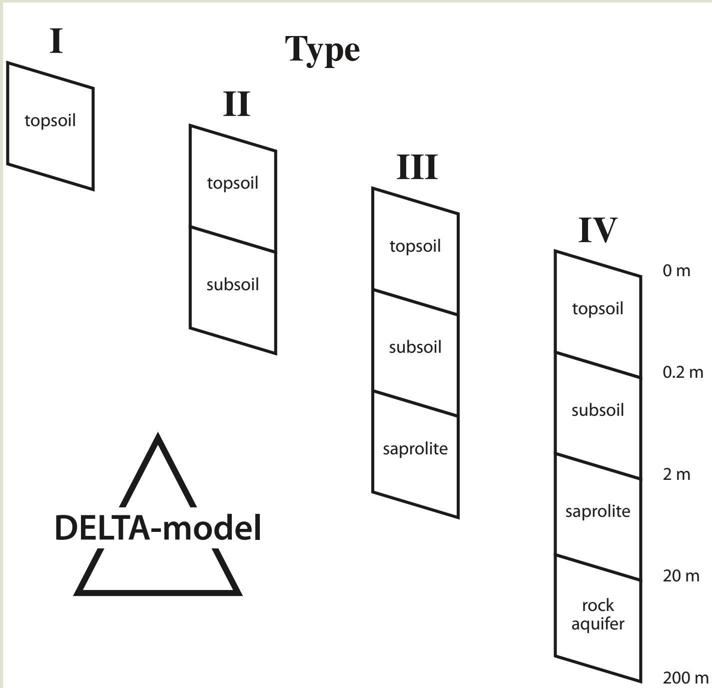

Fig. 11.1. Schematic Representation of Hydrologic Systems in Tropical Natural Forests. This figure indicates where different pathway systems dominate, including near-surface hydrologic pathways (Type I), lateral hydrologic pathways in the solum (A and B soil horizon; Type II), lateral hydrologic pathways in the saprolite (Type III), or lateral hydrologic pathways in a rock aquifer (Type IV). Example depths and the logarithmic depth scale are given. [Adapted with kind permission from Springer Science+Business Media: Chappell, N.A., et al. 2007. "Runoff Processes in Southeast Asia: Role of Soil, Regolith and Rock Type." In *Forest Environments in the Mekong River Basin*, 3–23. Eds. H. Sawada, M. Araki, N. A. Chappell, J. V. LaFrankie, and A. Shimizu, Springer Verlag, Tokyo. © 2007 Springer.]

Key Uncertainties and Research Opportunities

The preceding synthesis has highlighted several key research gaps and uncertainties related to both canopy hydrology and hydrologic pathways:

- **How can water budgets derived from eddy correlation and catchment balances be integrated to give a better understanding of the changes in forest evapotranspiration following disturbance and reforestation at tropical macroscales?** Understanding the evapotranspiration component of the tropical water cycle is of fundamental importance to ecosystem modeling. Although increasing, the number of locations with eddy flux observations above tropical forests still is limited. Consequently, most evapotranspiration estimates for tropical forests, in undisturbed and disturbed states, are derived from catchment water budgets (i.e., the difference between annual rainfall and annual stream flow per unit area) or the analysis of automatic weather station data (Zhang et al. 2001; Roberts et al. 2005). All these methods are now known to be prone to considerable error (Drexler et al. 2004; Burba and Anderson 2010). Error analysis and method intercomparisons thus are necessary for all new observational studies and as integral parts of any new data assimilation studies. Such analyses enable confidence within the findings of new syntheses of long-term estimates of evapotranspiration or the effects of forest disturbance or reforestation on regional evapotranspiration.

- **What is the depth of the dominant hydrological path mapped at each 100 km^2 location across the Humid Tropics? What saturated hydraulic conductivity distribution can be associated with this dominant path for each mapped location?** The pathways of water over and below the land surface regulate which strata (soil horizons, saprolite, and solid rock) provide the water and chemical resources that support tropical forests and associated faunal communities (including microbiology) and how nutrients are leached to rivers. In steep mountain environments, the dominant hydrological path may extend only to decimeters below the ground surface, but, within areas underlain by rock aquifers, it may be hectometers deep. Although

maps of the soil types covering the Humid Tropics are available, the hydrological functioning of each soil type (e.g., whether the flow is predominantly vertical or horizontal) is much debated, and there is often much variability within each soil type (e.g., McDonnell 2003; Chappell and Sherlock 2005; Chappell et al. 2007). Maps showing the presence of rock aquifers across the Humid Tropics are available (www.whymap.org), but maps of the extent of shallow saprolite layers are incomplete. Physics-based models of catchment hydrology that can predict the dominant hydrological paths normally are most sensitive to the model parameter of the saturated hydraulic conductivity. Within the Humid Tropics, observations of the saturated hydraulic conductivity typically are available only for very small volumes of soil or saprolite. It is now known that the values needed to parameterize models with grid elements much larger than the measured volumes are not easily derived from direct observations (Brooks, Boll, and McDaniel 2004). Much research is needed to understand how saturated hydraulic conductivity values appropriate for the parameterization of regional or global ecosystem models can be derived for the mapped soil, saprolite, and rock types across the Humid Tropics.

- **Can hydrograph shape be used to help determine the dominant hydrological path, (i.e., a lateral path via the soil, a saprolite layer, a fractured rock, or a rock aquifer) at gauged locations throughout the Humid Tropics?**
  The recession of a river hydrograph is an area-integrated expression of the dominant hydrological path or paths within a watershed. Watersheds where the water movement is dominated by shallow water pathways through the soil have rapid hydrograph recessions (i.e., minutes to hours). In areas underlain by major rock aquifers, the hydrological pathways are much deeper and the hydrograph recessions much longer (i.e., months). In areas where saprolite pathways or shallow rock fractures dominate, then the intermediate duration recessions dominate (Ockenden and Chappell 2011). Analysis of recession constants for many watersheds across the Humid Tropics should be undertaken systematically (Peña-Arancibia et al. 2010), as these findings have the potential to help develop the pantropical map of the dominant hydrological paths.

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