Forest Ecology and Management xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Long-term (33 years) rainfall and runoff dynamics in a tropical dry forest ecosystem in western Mexico: Management implications under extreme hydrometeorological events☆

Manuel Maass[a,*], Raúl Ahedo-Hernández[a], Salvador Araiza[a], Abel Verduzco[b], Angelina Martínez-Yrízar[b], Víctor J. Jaramillo[a], Geoffrey Parker[c], Fermín Pascual[a], Georgina García-Méndez[b], José Sarukhán[b]

[a] Instituto de Investigaciones en Ecosistemas y Sustentabilidad (IIES), Universidad Nacional Autónoma de México (UNAM), Morelia, Mexico
[b] Instituto de Ecología, Universidad Nacional Autónoma de Mexico (UNAM), Hermosillo and Mexico City, Mexico
[c] Smithsonian Environmental Research Center, MD, USA

ARTICLE INFO

Keywords:
Chamela
ENSO
Forest management
Hurricane
ILTER
Mex-LTER
Rainfall:runoff relationship
Tropical dry forest

ABSTRACT

Rainfall, runoff and sediment yield have been measured over three decades (1983–2015) in five contiguous small watersheds (12–28 ha) covered by mature tropical dry forest (TDF) at the Chamela Biological Field Station, UNAM, in the southern Pacific Coast of Jalisco, Mexico. Hydrological dynamics strongly drive the seasonal and inter-annual variability of TDF primary productivity, litter decomposition and nutrient cycling. Although the study region is constantly influenced by storms related to hurricane activity, they rarely make landfall. However, hurricanes have landed twice over a four-year period in the reserve: category 2 Hurricane Jova, in October 2011, and category 4 Hurricane Patricia, in October 2015. The long-term data has allowed to evaluate ecosystem's response to these two major hydrometeorological events, in the context of the historic rainfall/runoff pattern. The results showed that antecedent precipitation and rainfall intensity were the major factors controlling rainfall-runoff and soil erosion processes. The analysis also showed the timing of the onset of the rainy season was very regular but the length of the rainy season was quite variable. The highly variable rainfall pattern and high probability of intense storms at the onset of the wet season were linked with the vulnerability of TDF to soil erosion. Also, two types of recurrent and intense drought periods have been identified: the high inter-annual droughts; and the frequent within-wet season droughts ("canículas"). There is a clear influence of the "El Niño"-Southern Oscillation phenomenon (ENSO) on the study area, with lower annual rainfall during its hot phase, and higher annual rainfall during its cold phase ("La Niña"). The relevance of these findings is discussed in terms of forest ecosystem management practices in the region and its implications concerning the current climate-change forecast for the study area.

1. Introduction

Water has an important integrative role in most terrestrial ecosystems, making its dynamics a key aspect for ecosystem structure and functioning, and as a major controlling factor on ecosystem productivity (Chapin et al., 2002). Maintaining natural water dynamics has been an essential ecosystem management component and a requirement to reach sustainable productivity. Understanding hydrological processes in tropical dry forest (TDF) is particularly important since water is the major limiting resource in these ecosystems (Bullock et al., 1995; Dirzo et al., 2011). However, there is a paucity of literature concerning the hydrological characterization of TDF (Maass and Burgos, 2011). Studies of hydrological processes in TDF represent less than 1% of the published forest hydrology literature (Farrick, 2014).

There is a robust response of the hydrological cycle to global warming (Held and Soden, 2006). IPCC Report (2014) indicates that "*Changes in many extreme weather and climate events have been observed since about* 1950". Also, the report forecasts "*an increase in the number of heavy precipitation events in a number of regions*". Although Knutson et al. (2015) forecast fewer tropical cyclones globally in a warmer late-twenty-first-century climate, they project an increase in average cyclone intensity, precipitation rates, and the number and occurrence of

☆ Part of the Special Issue "Resilience of tropical dry forests to extreme disturbance events: An interdisciplinary perspective from long-term studies".

* Corresponding author.
E-mail address: maass@cieco.unam.mx (M. Maass).

http://dx.doi.org/10.1016/j.foreco.2017.09.040
Received 1 July 2017; Received in revised form 15 September 2017; Accepted 16 September 2017

very intense category 4 and 5 hurricanes. In Mexico, TDF regions are already experiencing extreme meteorological events. Álvarez-Yépiz, J.C.,Martínez-Yrízar, A., (2015) reported an extreme frost in 2011, causing unprecedented tree mortality in the most northern distribution of TDF of Sonora and Sinaloa. Also, they mentioned that hurricane activity in the Pacific coast of Mexico has increased significantly in the last decades. Seven hurricane events have struck the Jalisco Coast since 1949. An extreme one in Manzanillo (100 km south of Chamela) caused 1500 deaths in 1959. In 2011 for the first time since the Chamela TDF ecological monitoring started, the study site was directly impacted by Hurricane Jova (category 2). Four years later (2015), Hurricane Patricia made landfall, but with a much-stronger wind force (category 4; see Parker et al., this issue). This increase in hurricane frequency in tropical areas has triggered an interest to study the effects of extreme meteorological events and their implication for forest management and conservation.

TDF is the most extensive tropical ecosystem in the world, originally representing 42% of all tropical forests (Murphy and Lugo, 1986). Large areas of these forests are found in India, Africa ("miombo" forest), Australia, northeastern Brazil ("caatinga" forest), northwest Argentina ("chaco" forest) and along the Pacific coast of Mexico and Central America ("selvas bajas caducifolias"). In Mexico, TDF is well represented, covering originally $> 24 \times 10^6$ ha distributed along the Pacific coast, northern Yucatán Peninsula, Balsas Basin, southern tip of Baja California Peninsula, and large areas in Tamaulipas (Rzedowski, 1978; Trejo, 1998; Trejo and Dirzo, 2002).

Despite the biological and economic importance of TDF, it has seen deforestation at alarming rates, mainly by pasture-land expansion during the second half of last century. This has caused forest degradation, particularly in sub-humid areas of Latin America (Toledo, 1991) and disruption of ecosystem services (Maass et al., 2005). According to INEGI (2005 and INEGI 2013) 69.4% of the original TDF distribution has been already lost. Janzen (1986) considered TDF as one of most endangered major tropical ecosystems, and warned in the early 80 s, that less than 0.1% of the original tropical dry forest in Pacific Mesoamerica had real conservation status. This deforestation trend triggered an important TDF conservation process (e.g. Ceballos and García, 1995; Taber et al., 1997). However, in a more recent study, Miles et al. (2006) estimated that little over 1 million km^2 of tropical dry forest remained on earth. They warned that 97% was still at risk even though about 30% was under some form of protection (70% in South America) – they also noted that climate change was an important risk for TDF conservation.

To improve the understanding of the structure and functioning of TDF, and to develop ecologically sound management practices for its sustainable use, a long-term ecosystem research project was established in 1981 (Sarukhán and Maass, 1990; Maass et al., 2002) within a well-protected TDF of the Chamela Biological Station of the National Autonomous University of Mexico (UNAM). Since then, inputs, outputs and internal fluxes of water, energy, carbon and nutrients have been monitored on this ecosystem for more than three decades. The study site has been preserved from human perturbation. However, the forest is subject to the effects of natural disturbances such as droughts and hurricane activity, but not natural fires. The interest in extreme meteorological events in TDF research and monitoring, is also shared by land managers, as well as the inhabitants of the area.

A detail understanding of the TDF hydrology, especially the timing of rain onset and the possibility of droughts of several sorts, will help local land managers maximize productivity and avoid crop failures. Therefore, the aim of this paper is fourfold: (1) to quantitatively describe the long-term hydrologic dynamics of the TDF; (2) to evaluate its response to major hydrometeorological events (hurricanes); (3) to compare such response with the long-term patterns; and (4) to discuss some forest management implications in relation to extreme climatic events.

2. Materials and methods

2.1. Site description

The long-term study is being conducted at the Biological Station of UNAM located in the Chamela-Cuixmala Biosphere Reserve, 2 km inland from the Pacific coast of Jalisco, Mexico (105°W, 20°N). Five small watersheds (12–28 ha each) were selected as study units (for general features and location of the watersheds, see Martínez-Yrízar et al., this issue). All watersheds are under natural (without human perturbation) conditions and covered with tropical dry forest. Rainfall is highly seasonal and highly variable from year to year (annual range from 340.0 to 1329.0 mm). Mean annual rainfall is 800.4 mm (1983–2015), with 86.8% falling between June to October, and September (214.9 mm) is the wettest month on average. Mean annual temperature is 25.6 °C (1980–2015) with minor variation among years. Monthly mean minimum and maximum temperatures are 16.4 °C (March) and 32.6 °C (August), respectively. As a result of this climatic pattern, the potential evapotranspiration in the region is higher than precipitation during 10 consecutive months of the year, creating a high evapotranspiration demand and a substantial consumption of the available water through ecosystem latent heat fluxes (Maass and Burgos, 2011).

Except for isolated and incipient alluvial valleys and coastal plains, the topography is dominated by hills with mainly convex slopes of 15° to 60° and a range in elevation of 20–180 m (Maass et al., 1988; Cotler et al., 2002). Soils, identified as Entisols according to the Soil Survey Staff (2009), are young, often shallow (0.2–0.6 m depth), poorly structured and with an A and AC horizon (Solís, 1993). They are sandy loams in texture, neutral (pH 6.5), with a bulk density of 1.17 g cm^{-3}, and with low organic matter (2.4%). Phosphate is also low, whereas calcium is abundant (57.2 and 3,495.1 kg ha^{-1}, respectively). Total cation exchange capacity is 8.7 meq (Maass et al., 1988).

The predominant vegetation in the area is the tropical dry forest (Rzedowski,1978) mostly distributed on the hills and slopes. Tropical semi-deciduous forest occurs along the arroyos, riparian associations, coastal strands, mangrove swamps, and brackish lagoons in the low valleys (Lott, 1993). It is a highly diverse ecosystem with > 1000 spp. of vascular plants (Lott and Atkinson, 2002). Total above-ground phytomass in the slopes is 85 Mg ha^{-1} (Martínez-Yrízar et al., 1992). Long-term (1982–2009) average litter production varies among watersheds from 3.5 to 4.9 Mg ha^{-1} y^{-1} (Martínez-Yrízar et al., this issue) and the litter layer from 7.0 to 8.1 Mg ha^{-1} (Patiño, 1990). Mean stem density (dbh > 3.0 cm) is 2750 ha^{-1}, mean basal area is 17.6 m^2 ha^{-1}, and the average canopy height is 7 m. Leaf area index varies from 1.0 m^2 m^{-2} in April to 4.7 m^2 m^{-2} in September (Maass et al., 1995).

During the second half of last century, the tropical dry forest in the region has been subjected to intense transformation. Usually, the forest is burned after clearing with axe and machete. Maize is planted for about two years, and then replaced with grass for grazing (*Panicum maximum* Jacq. and *Cenchrus ciliaris* L.; De Ita, 1983). Soil erosion was measured in experimental plots covered by forest as almost negligible (less than 0.2 Mg ha^{-1} y^{-1}), whereas in the maize and grass fields rates can be as high as 130 Mg ha^{-1} y^{-1} (Maass et al., 1988).

2.2. Rainfall and runoff monitoring

Rainfall monitoring was initiated in 1983 and has been measured continuously using a calibrated Belfort bucket recording rain-gauge, at the Chamela Biological Station located within the 2 km^2 study area. Rainfall depth, duration and intensity values were extracted for each individual precipitation event, with a precision of 0.5 mm. It was considered a different rainfall event when recording stopped for > 2 h.

Standardized Precipitation Index (SPI; McKee et al., 1993) was used to detect intra-annual droughts (canículas). SPI values between 0.99 and −0.99 were considered 'near normal'; values between −1.0 to −1.49 as 'moderately dry', values between −1.5 to −1.99 as 'severely