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The role of Cloud Affected Forests (CAFs) on water inputs to dams ☆

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ABSTRACT

Cloud Affected Forest (CAF) environments are among the most threatened forest ecosystems of the planet. Yet, they are responsible for the supply of stable clean water, through dams, to many human communities across the tropics. Payment for Watershed Services (PWS) schemes can play a key role to mitigate CAF degradation in dam watersheds. However, a thorough scientific understanding of the hydrological role of CAFs in achieving dam performance goals is paramount to ensure the correct implementation of such financial mechanisms. By creating the most detailed dam census across the global extent of CAFs (The King's College London Tropical Database of Dams—KCL TDD) we explored the potential contribution of CAFs to water inputs to dams in order to inform implementation of regional PWS strategies. Results indicate that whilst CAFs cover only 4.4% of the tropical extent of dam watersheds they receive and filter almost 50% of the surface water balance over the same area. This remarkable finding reveals both, the vital role of CAFs in stable clean water supply to tropical dams, and the considerable opportunities to optimize the performance of dams by targeting the often limited resources to improved protection of CAFs in dam watersheds.

1. Introduction

Cloud Affected Forest environments (CAFs) as defined hydroclimatically by Mulligan (2010) are amongst the wettest environments on Earth and provide watershed services, such as the supply of water in quantity, quality and timing, which are likely to be important to many human communities throughout their pan-tropical extent (Bruijnzeel et al., 2010a,2010b,2006,2005; Jarvis and Mulligan, 2010; Mulligan and Burke, 2005a,2005b). Moreover, CAFs are also increasingly recognized as an important multifunctional ecosystem, which, in addition to high-quality water, offers a variety of ecosystem services such as carbon sequestration, biodiversity and scenic beauty (Aylward, 2005; Scatena et al., 2010; Bruijnzeel et al., 2010a). However, CAFs are heavily threatened by multiple anthropogenic pressures, such as for their conversion to pasture (Bruijnzeel et al., 2010a,2006; Mulligan, 2010; Mulligan and Burke, 2005a; Sáenz, 2007; Sáenz and Mulligan, 2007), and are likely to encounter further challenges from imminent climate variability and change (Nadkarni, 2010; Nair et al., 2010; Scatena et al., 2010).

Climatologically, cloud forests are defined as "forest affected by frequent and/or persistent ground level cloud" (Bruijnzeel et al., 2010a; Cavelier and Goldstein, 2009; Grubb, 1977). Cloud forests usually show structural and physiological adaptations to this cloud immersion. Mulligan (2010) modeled cloud forest presence globally using the Grubb (1977) definition and defined Cloud Affected Forests (CAFs) as those that are hydrologically affected by cloud immersion (i.e. receive higher precipitation and lower evapotranspiration). We used Mulligan (2010) hydroclimatic definition as such CAFs cover a much wider range of forest types, which are affected by fog immersion, and provide a more hydrologically relevant representation of these environments (Mulligan, 2010).

High cloud water interception and reduced Actual Evapo-Transpiration (AET) means that CAFs are likely wetter than their lowland counterparts across the tropics (Bruijnzeel et al., 2010a,2010b; Mulligan, 2010; Mulligan and Burke, 2005a). To illustrate this point Mulligan and Burke (2005a) indicate that CAFs regions alone may account for around 29% of the available tropical surface water balance. CAFs rainfall (1606 mm $year^{-1}$) exceeds the tropical average by 495 mm $year^{-1}$. Their surface

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Abbreviations: CAF, Cloud affected forests as defined by Mulligan (2010); PWS, Payments for Watershed Services (PWS) schemes; AET, actual evapotranspiration; KCL TDD, King's College London Tropical database of dams; WRD, World Register of Dams; WCD, World Commission of Dams; DDP, Dams and Development Project; CBCD, Brazilian Committee on Dams; MRC 2008), Mekong River Commission; GLWD, Global Lakes and Wetlands Database

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water balance (452 mm $year^{-1}$) is also 328 mm $year^{-1}$ higher than the tropical average. Deforestation of CAFs can then lead to changes in prevailing micro-scale hydrological regimes that affect the supply of water in quantity, quality and timing (Bruijnzeel et al., 2010,2006; Mulligan, 2010). Field studies have also indicated that the degradation of soil properties that accompanies CAF conversion can also hinder infiltration opportunities that support normal groundwater recharge regimes (Bruijnzeel, 2004; Bruijnzeel et al., 2010a,2005; Grip et al., 2005; Tobon et al., 2010; Zimmermann and Elsenbeer, 2008).

Payments for Watershed Services (PWS) schemes are so-called soft interventions for more integrated watershed management and are proliferating, especially in developing countries of the tropics. It has been commonly pointed out that while being an attractive intervention that can improve watershed conservation, PWS schemes also hold potential to provide a diversified income for rural development in these countries (Alix-Garcia et al., 2008).

However, the success of Payments for Watershed Services (PWS) schemes depends on managing the balance between growing human demands for watershed services and for agricultural land. As human water demands from CAFs are high and these ecosystems also have a significant biodiversity value (Bruijnzeel et al., 2010b,2005; Bubb et al., 2004; Bubb and Das, 2005; Scatena et al., 2010), some of the most well known PWS schemes have focused on prioritizing conservation of CAFs over the expansion of the often low opportunity costs agricultural activities characteristics of the complex terrain, where CAFs are found (Alix-Garcia et al., 2008; Bruijnzeel et al., 2010a; Kroeger and Casey, 2007; Landell-Mills and Porras, 2002; Mulligan et al., 2009; Mulligan et al., 2010a,2010b; Porras et al., 2008; Tognetti et al., 2010,2005). Many of those schemes have also focused on improving the performance of dams to meet current and future demands from their services (Aylward, 2005; Aylward and Echevarria, 2001; Porras et al., 2008; World Commission on Dams, 2000).

With dam development increasing in tropical areas, in order to meet the growing demands for cheap and clean energy (International Commission on Large Dams, 2003; Ledec and Quintero, 2003; Mulligan et al., 2009; World Commission on Dams, 2000), from the same landscapes in which the agricultural frontier is still growing, the development of PWS schemes to protect the watersheds of dams is likely to increase (Mulligan et al., 2010a, 2010b). The sound implementation of PWS schemes across the tropics could bring significant opportunities to make CAF conservation viable upstream of existing dams through targeted economic compensation in return for the watershed services provided. A careful scientific understanding of the hydrological role of CAFs in achieving dam performance goals is nonetheless paramount to ensure the correct implementation of such mechanisms (Aylward, 2005; Aylward and Echevarria, 2001; Bruijnzeel et al., 2010b; Mulligan et al., 2009,2010a,2010b; Palmieri et al., 2001; Porras et al., 2008; Southgate and Macke, 1989; World Commission on Dams, 2000).

However, there is currently no systematic data framework to provide a spatially explicit assessment of the key CAFs supplying water to tropical dams. Existing information on the hydrological value of CAFs to dams is highly fragmented (Aylward, 2005; Sáenz, 2007; Sáenz and Mulligan, 2007) and site specific. Sophisticated modeling studies to explore the distribution of CAFs globally have been carried out (Mulligan, 2010) but have yet to be applied to the assessment of the hydrological value of CAFs to dams. The fact that a consistent dam census downstream of CAFs has been lacking prevents the assessment of CAFs conservation opportunities for sustaining water security in the tropics (International Commission on Large Dams, 2003; Mulligan, 2010; Mulligan and Burke, 2005b).

Here we first present a newly created tropical dam census across the global extent of CAFs (KCL TDD). We follow with an analysis of the potential hydrological contribution of CAFs to dams on a pan-tropical scale calculating and using the watersheds of dams as the spatial analytical framework. We focused on dams because these are points in the landscape at which hydrological services are converted to economic outputs.

2. Methods

The King's College London tropical database of dams (KCL TDD), geodata.policysupport.org/dams; with data for the Amazon basin featured by Tollefson (2011), covers all tropical and subtropical areas from 23.5 N to 35.5 S as there is evidence that most CAFs are found within these latitudes (Mulligan and Burke, 2005a). The database considers large dams, as defined by International Commission on Large Dams (2003), but also smaller dams with standard minimum physical reservoir dimensions of >500 m long and 125 m wide, and are digitized from LANDSAT and higher resolution imagery (Fig. 1). The population of dams smaller than this threshold is also likely to be very large but is poorly documented (Lehner et al., 2011).

The KCL TDD was built and completed in 2009, but is continuously updated. It was created by manually digitizing dams on high resolution remote sensing imagery (Google, 2009). Effective digitization is provided by an innovative Google Earth based GEOWIKI tool developed at King's College London to allow creation of large geo-referenced databases (Mulligan, 2008). The observation of dams was assisted on a national scale by information provided by secondary sources, which include the World Register of Dams (WRD) (International Commission on Large Dams, 2003), the World Commission of Dams mandate (World Commission on Dams, 2000), the Dams and Development Project (DDP) (United Nations Environment Program, 2007), the Brazilian Committee on Dams (CBCD) (Brazilian Committee on Dams, 2008), Venezuelan Committee on Dams (Comité Venezolano de Grandes Presas (2008)), the Mekong River Commission main streams dam map (Mekong River Commission, 2008), the geo-referenced database of African dams (AQUASTAT, 2006) and the Global Lakes and Wetlands Database (GLWD) (Lehner and Döll, 2004).

The spatial resolution of global freely available imagery can vary significantly from region to region and this affects the accuracy of the digitizing process. Imagery in Google Earth, for instance, has spatial resolution varying from <1 m (IKONOS, QUICKBIRD, SPOT and aerial photographic sources), found in large cities and in economically developed settings (with around 30% terrestrial coverage) (Google, 2009), to 30 m (Landsat 5) in less developed areas like tropical countries, where cloud cover is often also a problem. To provide an indication of error (differences in dam density) introduced by digitizing from sources with differing spatial resolutions, we implemented the following validation approach.

The approach consisted of digitizing observable dams in Landsat 30 m images for a given area (25 km^2) and then independently digitizing the dams for the same area but using the higher resolution imagery sources (1 m) available in Google Earth. The difference between the number of dams digitized with the different spatial resolutions of available imagery for the same tiles were used as an indicator of the potential number of dams not represented in the database in areas where only low resolution imagery is available. This validation was performed with the use of the Terrascope portal, which is a Google Earth implementation of the Landsat archive with images up to the year 2000 (Mulligan, 2007). Terrascope provides the same Landsat data as