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Hydrometeorology of the Dhofar cloud forest and its implications for groundwater recharge

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ABSTRACT

Study region: The Dhofar mountains are located on the Arabian Peninsula in Southern Oman. Unlike other regions of Oman, the Dhofar mountains have an annual monsoon season that results in a semi-arid cloud forest. The region highly depends on groundwater resources and the Dhofar mountain range is the major recharge area for the Salalah coastal plain.
Study focus: Forests in cloud-impacted areas can harvest cloud-water droplets in addition to receiving rainfall. The forest interception and recharge relevant net precipitation are investigated by ecohydrological studies. These studies are, however, limited to the point or experimental plot scale and to particular tree species. Groundwater studies, in contrast, are often linked to catchment or groundwater aquifer boundaries and are therefore calculated at meso- to regional scale. To be able to utilize findings from ecohydrological site studies for regional groundwater studies we regionalize field site studies through cloud forest distribution and rainfall interpolation in a semi-arid, data scarce region heavily dependent on groundwater resources.
New hydrological insights for the region: Our results are a cloud forest precipitation scenario that quantifies the additional rainfall gained through cloud water harvesting by the cloud forest. In comparison to interpolated rainfall the precipitation available for recharge within the Dhofar mountains increases by 20%. Considering a recharge-precipitation ratio calculation the recharge ratios in the region are up to 24% for highly forested areas.

1. Introduction

The availability of sustainable water resources is an essential concern in arid and semi-arid regions. On the Arabian Peninsula water withdrawal is estimated to be more than five times higher than renewable water (Frenken, 2009). However, the estimation of such numbers is based on extremely sparse data and subject to large uncertainties. Using global atmospheric reanalysis models Lorenz and Kunstmann (2012) demonstrated the effect of sparse rain gauge distributions on the uncertainty of daily rainfall estimated by the reanalyses. As rainfall determines current groundwater recharge, the recharge zones and their functioning is of paramount importance in quantifying renewable water resources.

The Dhofar mountain range of Oman is one of these recharge areas and supplies both the Nejd desert region to the North as well as the Salalah coastal plain, Oman's second largest city, to the South with groundwater recharge. The Dhofar mountains feature a semi-arid seasonal cloud forest fed by the annual Khareef (monsoon) season (Hildebrandt and Eltahir, 2006). Besides the annual monsoon

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the region is subject to strong cyclonic events (up to 400 mm within a few days) that occur irregularly every 2–6 years. Strauch et al. (2014) analyzed the isotopic signatures of rainfall, spring discharge, and groundwater. Results show that groundwater recharge from the Dhofar mountains to the Salalah coastal plain is mainly linked to monsoon rainfall. This is also supported by the observations of (i) higher soil moisture during the monsoon than during and after cyclone rainfall events (Hildebrandt et al., 2007), and (ii) greater surface runoff during cyclonic rainfall due to infiltration excess flow vs. little to no surface runoff during the monsoon.

Forests intercept and redistribute precipitation into different components: throughfall, and stemflow (Levia et al., 2011). The sum of throughfall and stemflow determines net precipitation, the amount of water available below the canopy. Water that is intercepted by the canopy is being evaporated and therefore mostly results in a loss of water (Carlyle-Moses and Gash, 2011). Net precipitation is classically measured by budgeting measurements of throughfall, stemflow, and open rainfall (Friesen et al., 2015). During the Khareef season in Southern Oman, precipitation is available as (i) rainfall, and as (ii) fog, also called ‘horizontal precipitation’. Horizontal precipitation is mainly a turbulent process where cloud droplets are mixed inside the canopy and are intercepted by the vegetation (Hildebrandt et al., 2007; Shuttleworth, 1977). Whereas rainfall is recorded via rain gauges, the amount of fog is usually not measured. In particular, trees have the ability to harvest cloud water more efficiently than lower vegetation, yielding higher amounts of horizontal precipitation in addition to rainfall (Hildebrandt and Eltahir, 2008). When fog moves through the canopy, water accumulates at the leaves and branches, and then either evaporates, drips off as throughfall, or flows down the stem as stemflow. Cloud forest hydrology has been extensively studied (Bruijnzeel et al., 2011; Holwerda et al., 2010), especially in tropical montane cloud forests.

The importance of cloud or fog interception to groundwater recharge has also been shown by Clark et al. (1987) for the Dhofar region, by Ingraham and Matthews (1988) for Kenia, and by Sawaske and Freyberg (2014) for California. The annual monsoon season in Dhofar, through its interaction with the vegetation (Bawain, 2012; Hildebrandt et al., 2007; Hildebrandt and Eltahir, 2007), facilitates survival of the Dhofar cloud forest. Also, through forest canopy redistribution, net precipitation is spatially heterogeneously distributed in throughfall and stemflow, whereas the latter is especially important for infiltration and recharge (Germer, 2013; Kacimov et al., 2010; Liang et al., 2011; Schwärzel et al., 2012). This is further emphasized by the fact that stemflow in the Dhofar cloud forest can reach up to 40% of net precipitation (Bawain, 2012) which even on a global scale is amongst the highest recorded stemflow contributions (cf. Levia and Frost, 2003).

Forest interception studies, which are required to assess interception and quantify the recharge relevant net precipitation are, however, often only possible at point or experimental plot scale and are limited to the studied tree species. Groundwater recharge and consequently also the input data to recharge models, in contrast, are required at relatively large scales, e.g. linked to hydrological catchments or groundwater aquifer boundaries, and thus is located at the other end of the spatial scale (Scanlon et al., 2002). Only few studies provide interception estimates on a large, global scale (Miralles et al., 2010; Murray, 2014), however, those ignore processes like horizontal precipitation and are therefore not suitable to translate the local eco-hydrological processes into recharge-relevant processes.

Studies regarding the precipitation in Oman exist on a national scale and are often limited to two or three rainfall stations in the study region (Al-Ajmi et al., 2013; Kwarteng et al., 2009).

In this study, we use data from 24 rainfall stations for the Dhofar region that allowed us to capture the variability across the mountain range and the coastal region and enabled us to produce daily, interpolated rainfall from 1992 to 2014. Satellite data for vegetation and elevation were used to derive could forest cover and extent.

Assumptions that were used to incorporate the cloud forest in a precipitation scenario were taken from previous studies. The main objectives of this study are to separate the monsoon rainfall relevant for the coastal plain recharge, to interpolate the monsoon rainfall, to generate an interpolated rainfall dataset including cloud forest impact, and to provide a basic groundwater balance based on the two rainfall datasets and groundwater recharge-precipitation ratio estimates.

2. Data and methods

2.1. Site description

The Dhofar mountains are located in southern Oman and act as a boundary between the desert region (Nejd) to the North and the Salalah coastal plain, including Oman's second largest city, to the South (Fig. 1) extending for almost 300 km into Yemen to the southwest. The Dhofar mountains are a crescent shaped coastal mountain range that encompasses the coastal plain around the city of Salalah. The coastal plain is about 15 km wide at its broadest point and 60 km long. From the flat coastal plain, the elevation rises abruptly in the mountains to about 900–1300 m a.m.s.l. in the study region. Jebel Samhan (outside the study region) has an elevation of about 1700 m a.m.s.l.

Groundwater recharge from the mountains feeds the coastal aquifer that is intensively used for agriculture and municipal water use. Precipitation can be subdivided into monsoon precipitation and cyclone events. The monsoon season occurs from mid-June to mid-September and is characterized by low intensity rainfall and drizzle (< 10 mm day^{-1}) and dense fog along the mountain range (visibility down to < 5 m, personal observation). During the monsoon season an inversion layer develops above the mountain crest that holds the clouds on the southern side of the mountains (Abdul-Wahab, 2003; Hildebrandt et al., 2007). Cyclonic rainfall events occur irregularly between 2–6 years (cf. 3. *Results*) for a couple of days and yield high rainfall amounts of up to 400 mm (Kwarteng et al., 2009). The mountainous land cover ranges from cloud forests (tree heights < 10m), cropland and grassland to bare rock. Soils are shallow with a depth of 0.5–1 m (Friesen et al., 2011). Next to its natural, botanical, and hydrological value (Bawain, 2012; El-Sheikh, 2013) the cloud forest also has a high economic value as the monsoon season in Dhofar is a touristic hotspot throughout the