Remote Sensing-Based Water Balance Modeling for Drought Assessment in Mediterranean Protected Forest Areas

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INTRODUCTION

Drought represents one of the most impactful extreme climatic events affecting forestry management and conservation of protected natural areas. In the Mediterranean basin, this phenomenon is particularly relevant due to forest ecosystem vulnerability to climate change. Forest expansion from afforestation of former croplands alters water balance at local and regional scales, increasing wildfire risk and decreasing water flow necessary to maintain riparian habitats. Precise quantification of water balance and evapotranspiration (ET) is fundamental for understanding hydrological dynamics and establishing adaptive management strategies. This study estimates regional surface water balance in Montseny Biosphere Reserve - Natural Park (RB-PNM) through remote sensing ET analysis using Sentinel data (2017-2022) and Terra/Aqua MODIS data (2000-2022), enabling identification of severe drought periods and evaluation of their impacts on long-term monitored forest catchments.

STUDY AREA

The RB-PNM is located in northeastern Iberian Peninsula. Water balance evaluation focuses on the experimental Castanya catchment containing two instrumented basins with over 30 years of records: TM0 (2.05 km²) and TM9 (0.05 km²) catchments. Both are characterized by Mediterranean mountain forest ecosystems: holm oak forests (*Quercus ilex*) (85%), beech forests (*Fagus sylvatica*) (10%), and sub-alpine shrublands (5%). Their altitudinal diversity makes them representative sites for evaluating hydrological response to drought events.

MATERIAL AND METHODS

Instantaneous ET estimation used the TSEB (Two-Source Energy Balance) model [1]. The SenET framework was implemented using pyTSEB with Sentinel-2 data (20m resolution, 2017-2022) and MODIS data (1000m resolution, 2000-2022), validated by [2] and [3], repectively, generally presenting RMSE ≤1 mm·day^{-1}. Spatial precipitation was estimated through multiple regression using meteorological station data. Surface water balance was calculated as P-ET for each hydrological year, with anomaly time series generated to identify deficit or surplus years.

RESULTS AND DISCUSSION

ET estimates showed RMSE values ≤1.1 mm·day^{-1}. Aqua MODIS achieved best results (0.8 mm·day^{-1}), followed by Terra MODIS (0.9 mm·day^{-1}) and Sentinel-2 (1.1 mm·day^{-1}). Temporal analysis (2017-2022) showed decreasing ET trends while potential ET increased, evidencing increased atmospheric evaporative demand do to a severe drought affecting the study area. Surface water balance (2000-2022) revealed significant variability, oscillating between deficits exceeding -300 mm·year^{-1} and surpluses exceeding 700 mm·year^{-1}. Hydrological years 2007-2008, 2011-2012, and 2021-2022 presented pronounced negative anomalies. Anomaly analysis identified two severe drought events: the first initiated in 2006-2007 with anomalies reaching -500 mm, and the second in 2021-2022 with similar magnitude, extensively affecting RB-PNM. All three sensors consistently captured these events, reinforcing estimation robustness.

CONCLUSIONS

SenET framework was successfully applied in RB-PNM using Sentinel and MODIS data, obtaining mean RMSE ~1 mm·day^{-1}. Surface water balance anomaly analysis clearly identified severe drought periods in 2006-2007 and 2021-2022, providing valuable information for adaptive forestry management in Mediterranean protected areas. Results highlight remote sensing utility for continuous monitoring of water availability in forest ecosystems

vulnerable to climate change. Future research will focus on improving ET modeling through local parameterization, higher resolution reanalysis data (ERA-Land), and extending analysis using Landsat data (30m) from 1984 to present.

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Table 1. ET Evaluation in the Castanya Experimental Catchments by water year using Sentinel, Terra and Aqua data. RMSE in mm·day^{-1}

		Water year												
		2000 - 2001	2001 - 2002	2007 - 2008	2008 - 2009	2009 - 2010	2011 - 2012	2012 - 2013	2014 - 2015	2015 - 2016	2016 - 2017	2017 - 2018	2021 - 2022	Avg
RMSE	Sentinel											1.4	0.9	1.1
	Terra	0.5	0.3	1.2	1.2	1.3	0.5	0.6	0.8	1.1	0.8	1.5	1.1	0.9
	Aqua			0.6	0.9	1.2	0.2	0.4	0.6	0.8	0.6	1.4	0.9	0.8

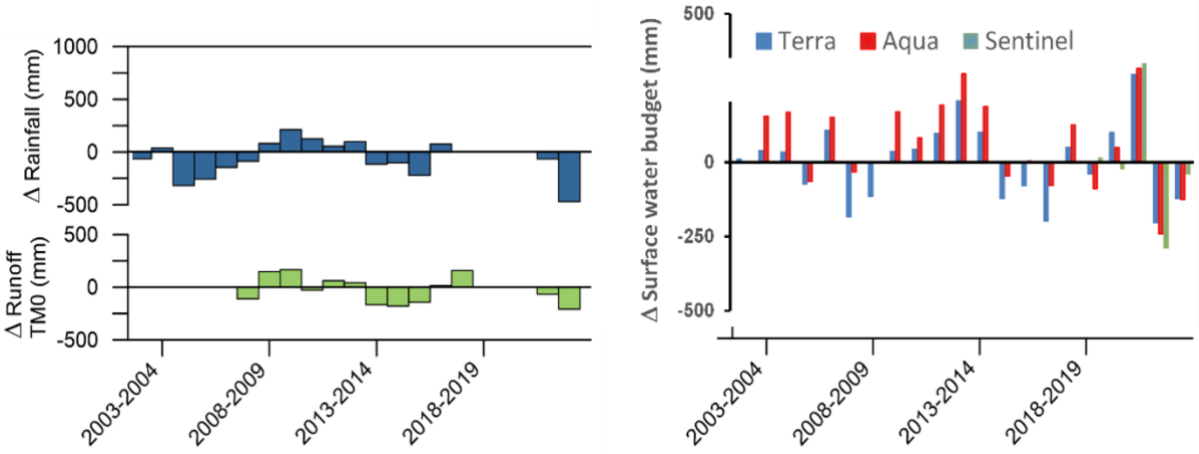

Fig. 1. Anomalies of runoff, precipitation and water balance calculated with MODIS and Sentinel-2 data and GIS modeling of precipitation in the Castanya experimental watersheds for the period 2000-2022.

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