Ovidius University Annals Series: Civil Engineering, Year 27, 2025 I
DOI: 10.2478/ouacsce-2025-0001

Environmental hydrology of water balance analysed by statistical modelling using Python

Lemenkova Polina [1*]

1* University of Bologna (corresponding author, e-mail: polina.lemenkova2@unibo.it)

Abstract – **This work presents the use of remote sensing data for hydrological and environmental analysis with a case of Dolomites Mountains, north Italy. The data includes remote sensing based micrometeorological measurements key hydrological parameters to calculate vertical turbulent fluxes within atmospheric boundary layers in coniferous forests. The period of measurements covered data from 2015. The operational workflow included statistical data processing in which the data were classified into categories of evapotranspiration, temperatures, precipitation, water pressure deficit and radiation obtained from various land cover types. The approach was implemented with aim at climate change and hydrological research and implications in forest ecohydrology in European Alps.**

Keywords – data analysis, environment, modelling, Python, statistical analysis.

1. Introduction

The effective measures of nature conservation, protection of mountainous landscapes and biogeographic heritage depend on analysis of climate-meteorological factors that lead to response of forest to changing climate and as a result, land cover changes [1]-[4]. These include the analysis of the hydrological setting, climatic parameters and topographic structure (terrain ruggedness, drainage density, slope curvature) climate and hydrological setting, and anthropogenic activities [5]-[7]. One of the key components of environmental forest monitoring is the observation, monitoring, and characterization of changes in land cover, in which satellite images play an essential role [8]-[10].

Hydrological and environmental measurements using remote sensing and Eddy covariance data present a reliable source of ecological information for monitoring Alpine forests [11]. Thus, micrometeorological observations provide data on vertical turbulent fluxes of water, carbon, and energy between forest ecosystems and the atmosphere [12]. The remote sensing (RS) data can then be used to validate and scale up these measurements to detect changes in forest behaviours under climate change and forecast possible changes in land cover types caused by environmental, climate and anthropogenic effects [13]-[15].

The effectiveness of the RS data for environmental forest monitoring is explained by the flexibility and availability of data. As a robust source of information with specific optical properties, satellite images can be processed using advanced cartographic methods to obtain information on land cover types. Since features of land cover types on the Earth have different spectral reflectance values, image classification enables to identify them using digital signatures of the satellite images. Observation, monitoring, and characterisation of land cover change are among the fundamental elements of environmental forest monitoring in which RS has a significant role.

Time series analysis of the statistical and RS data enables to detect climate-hydrological and environmental interactions in forest ecosystems. Specifically, such complex integrated analysis support modelling changes and recognise modified patches within the landscape structure, as reported in many relevant studies. Therefore, the extraction of these features from the RS signals recorded during the Eddy covariance and Earth monitoring data provides an essential tool to detect landscape dynamics.

Hence, the georeferenced and environmental datasets present an important information source for analysis of forest vegetation since it enables to model plant diversity changes in a long-term scale . Such time series analysis enables to compare current and previous state of the landscapes using cartographic data analysis and visualization which can be used for environmental monitoring, assessment of forest health and prognosis of possible further development of forest ecosystems and support hydrological research.

2. EXPERIMENT DESCRIPTION

Modelling of data was performed using Python libraries, such as Matplotlib, Numpy, Pandas. To classify meteorological and hydrological data, two types of approaches were carried out. The first is fieldwork data collection classification based on the Eddy covariance approach of measuring fluctuations. Eddy covariance measures the fluctuations and key hydrological characteristics such as evapotranspiration, temperature, precipitation, water pressure deficit and radiation obtained from coniferous forest stands with different ages: forest with old trees (> 200 y.o.) and forest with young trees (< 30 y.o.)., Table 1

Table 1 Meteorological parameters used for statistical modelling

Period	nr days	P	ET	Throughfall	Stemflow	Interception
young forest (trees of < 30 y.o.)						
dry	78	1.3 ± 1.8	350	2.6 ± 3.3	0.0	-1.3 ± 3.3
fog	8	0.1 ± 0.2	26	0.2 ± 0.0	0.0	-0.0 ± 0.2
fog+P	42	460 ± 35	110	292 ± 26	1.0	167 ± 36
rain only	34	132 ± 21	147	47 ± 11	0.1	85 ± 19
old forest (trees of > 200 y.o.)						
dry	78	1.3 ± 1.8	350	0.6 ± 0.2	0.0	0.7 ± 1.4
fog	8	0.1 ± 0.2	26	0.1 ± 0.0	0.0	0.1 ± 0.2
fog+P	42	460 ± 35	110	216. ± 11	0.8	242 ± 29
rain only	34	132 ± 21	147	36 ± 3	0.2	97 ± 16

Various land cover types of coniferous landscape were analysed using feature characteristics based on the signals of Eddy covariance tower. Water components from 2019-5-30 (DOY 150) until 2019-11-07 (DOY 311) at canopy level are presenetd in Table 1. It shows data based on daily observations divided into dry and precipitation periods. Precipitation measured inside and outside the forest (minor amount of precipitation during "dry" period because periods were defined based on the outside climate station alone), throughfall and stemflow measured with automatic tipping gauges, storage/interception calculated as P - Tf - St.

The second approach is data modelling, analysis and classification performed using several libraries of Python, technically realised in MacOS computer. Python's based data modelling included four algorithms embedded from Python's statistical libraries: box plots, correlation graphs, stankey plot and others. These models have been implemented to detect subtle changes in forest hydrology (evapotranspiration) as a response to changed climate parameters suc has temperature, precipitation, water pressure deficit and radiation. Diverse land cover types (old and young conifersou trees) were key study objects and their responses differed in varied climate-environmental conditions over study period.

3. RESULTS AND SIGNIFICANCES

The results were derived from the Python-based data modelling and showed different vegetation conditions in spring and autumn periods in central Dolomites, northern Italy. In hydrology, oversimplifications are accepted widely, because measurements of the water balance components include uncertainties. In ecohydrology, the latter is overcome by separating evapotranspiration into evaporation from surfaces inside the forest and transpiration by the vegetation, as shown in Python-based models, Figure 1.

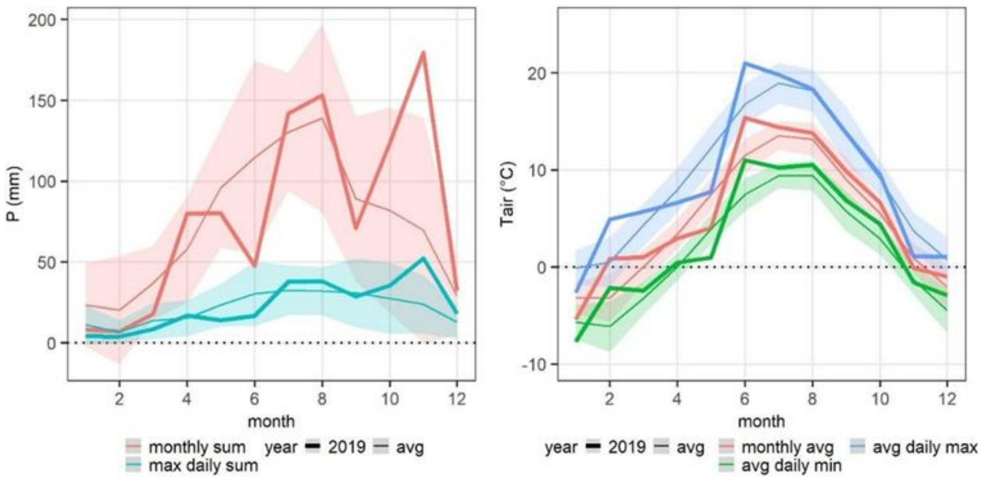

Fig. 1 Average monthly precipitation (monthly sum and maximum daily sum) and temperature (monthly average and average daily maxima and minima) for 2019 (thick line) and for the period from 1999 – 2019

Tree transpiration and soil evaporation can be measured directly through sapflow sensors and for instance canopy chambers, evaporation from canopy interception can still only be estimated indirectly or modelled. Thus, there are still major uncertainties, for example, concerning the rate of wet canopy evaporation estimated from eddy covariance measurements or as the differences between precipitation, throughfall and stem flow, or those using the conventional Penman-Monteith-equation by a factor of two or more.

3.1. Forest age as potential climate regulator

Apart from the physiological aspect of water use by the plant, the capacity of the intercepted water to act as a climate regulator at a local scale and the mesoscale is climatologically relevant. One millimetre of water at 20 °C represents 44.2 W m-2 of latent heat, which is emitted in place of sensible heat, thereby reducing the temperature and increasing the availability of water vapour in the air. The role of fog is mainly to sustain this positive feedback in the water cycle, favouring the presence of dense vegetation and lichens, and increasing the availability of water vapour, Figure 2.

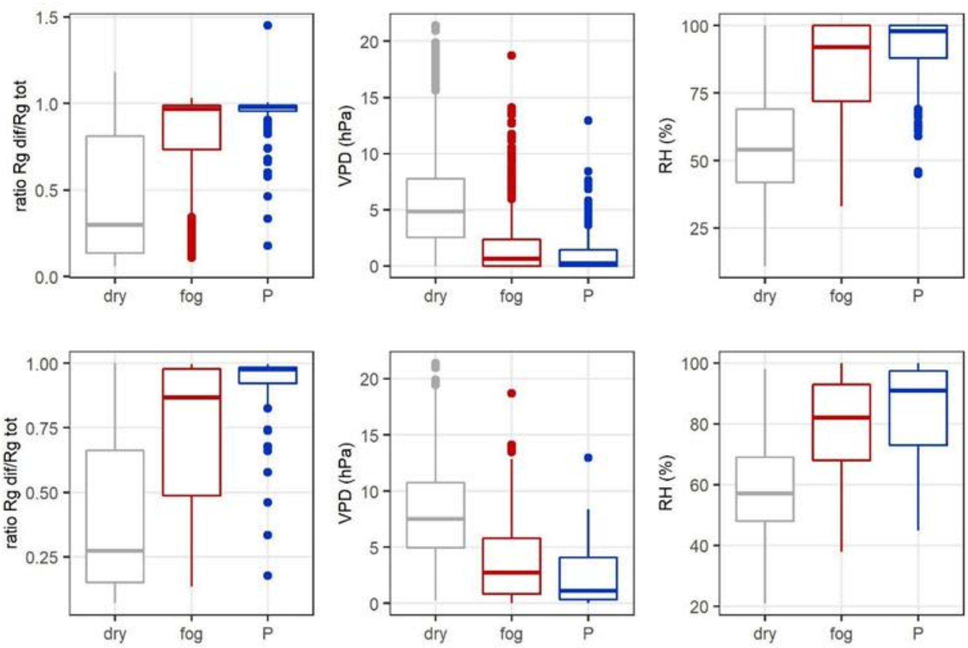

Fig. 2 Meteorological conditions (ratio of diffuse to total global radiation, vapor pressure deficit VPD, and relative air humidity RH) during periods with fog (less than 1 km visibility), precipitation, and dry conditions (dry) from January 1st until August 30th 2015 (top row) and from May 25th until August 30th 2015 (bottom row)

3.2. Hydrology of the Alpine Forest with fog as the missing tie

Though the water input through fog-only events at our site remained unknown, fog clearly contributed to mixed fog and rain precipitation when it was estimated to cause 24% of additional throughfall compared to rain only events. Thus, our current findings reveal fog as the missing tie to understand not only soil water recharge during days with mixed precipitation but the decrease of evaporative conditions during dry period, Figure 3.

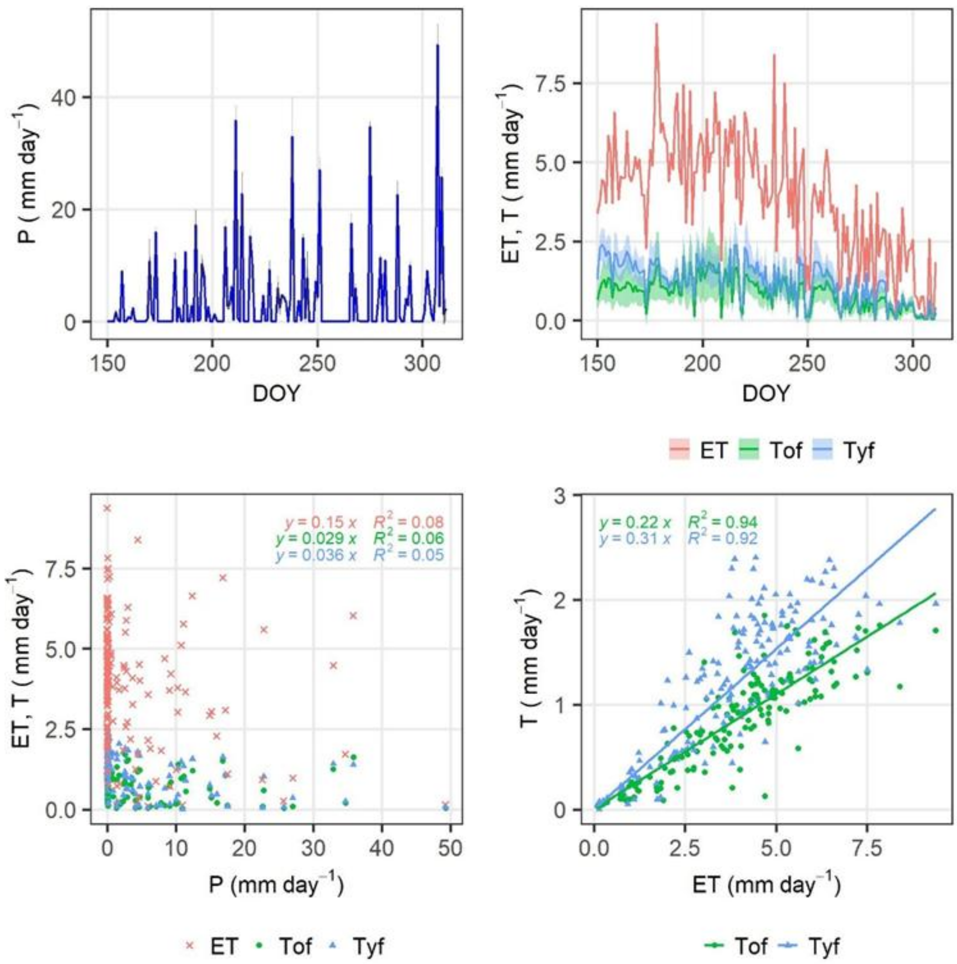

Fig. 3 Figure 5 (above) Time course of daily precipitation (P, top left in continuous line for clarity) as well as daily evapotranspiration measured with eddy covariance (ET) and daily transpiration for the old (Tof) and young (Tyf) forest upscaled from sap flow measurements (top right). (below) Correlation of daily ET, Tof, and Tyf with daily P (bottom left) and correlation of daily Tof and Tyf with daily ET

Here, we quantified the frequency of fog events in a subalpine coniferous forest in the Italian Alps and assessed the hydrological balance at basin and canopy scales by combining different measurement approaches. The difference between water input as rain and snow (without fog) and water output as evapotranspiration and water discharge, plus the variation in the soil water content, was 25 mm, within the uncertainty range of the measurements. This study revealed that fog combined with rainfall the same day, as mixed precipitation, contributed to higher throughfall, which in turn contributes to higher net precipitation (soil water recharge, in absence of runoff) and evaporative conditions inside the canopy, Figure 4.

Fog plays important role in water balance during days with mixed precipitation, maintaining for several days a high relative humidity inside the dense coniferous crowns composing the forest. This helped the trees to maintain a large amount of leaf area, and the filamentous lichens to grow in the upper part of the canopy.

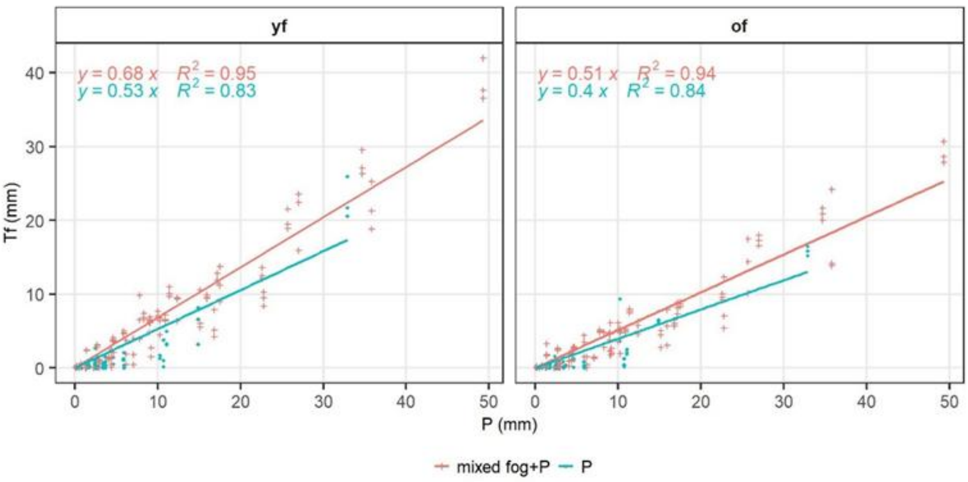

Fig. 4 Throughfall versus precipitation during mixed precipitation (mixed fog+P) and rain-only (P) events in the young (yf) and old (of) forest

These two features led to a large capacity of the crown, particularly in the mature coniferous forest, to intercept liquid precipitation, release only a small amount of precipitation to the soil and eventually to runoff, sustaining local ET with an associated reduction of the sensible heat flux. However, how much fog was intercepted by the canopy remains open for further research.

3.3. Water partitioning and balance at catchment level

We observed several differences in the ecosystem water partitioning at the catchment level for the 5-month measuring period, between the young (left plot in Fig. 8) and old stand (right plot). Throughfall and transpiration were higher in the young forest. Consequently, interception which was calculated as the residual of total P minus Tf minus Sf was lower in the young stand.

As intercepted water eventually evaporates back to the atmosphere, interception accounted for a major part of ET (54% in the old forest and 33% in the young forest). Evaporation is a part of the water cycle and provides a shortcut for precipitation water to return to the atmosphere without having to pass through the soil or the living parts of plants. This partially explains the low transpiration/ET ratios mentioned in section 3.1. The evapotranspiration of soil and understory was calculated as the residual of ET (Eddy covariance) - T - I, and was higher in the young stand, where the interception was much lower. An independent measurement of soil/understory ET using small-scale lysimeters or canopy chambers could provide additional information.

The ratios of transpiration measured with sap flow to evapotranspiration from eddy covariance (T/ET = 22% for of, 31% for yf) or total precipitation (T/P = 24% for of, 34% for yf) ratio were low for both stands, compared with those in other conifer forests examined in the literature where T/ET, T/P, and T/potential ET ratios range from 15% to 75%. On the other hand, our high ratios of interception to precipitation (I/P = 54% for of, 33% for yf) and ET (I/ET = 51% for of, 31% for yf) were in the upper range compared to I/P values of 17–45%.

4. CONCLUSIONS

In this study, we quantified the capacity of the forest to intercept water in the canopy, and we provided an estimate of this capacity in the two different forest stands, a 200-year-old and a young, 30-year-old stand. The higher water storage capacity of the old stand did not depend on the LAI, which was almost identical in the two stands, but on the other structures, mainly epiphytes. Such organisms, typically represented by filamentous lichens, such as Evernia divaricata and Pseudevernia furfuracea, were relevant for the water cycle in the old section only and had a water-holding capacity of 0.6 mm for each precipitation event. The relevance of this interception capacity was particularly high when precipitation was light (based on field observations). In this case, the liquid water was used to refill the canopy and soil reservoirs, without being lost as runoff. This large amount of water intercepted by the canopy, which represents most of the liquid precipitation in the old forest stand, is then locally re-emitted as evaporation without stomatal control. In addition, in some ecosystem types, it has been shown that part of this water and fog can be directly taken by the plant for its needs (Burgess and Dawson, 2004).

In a hydrological and hydrogeological perspective, this study indicated that natural forests play a key role in dampening heat extremes above vegetated terrestrial ecosystems. It also attributes to fog and cloudiness the role of linkage in the positive feedback between the presence of forests and cool and humid meteorological conditions. The vegetation of mountain regions, whose distribution is driven by the change of climatic and soil conditions along elevation gradients but also influenced complex (micro-) topography, is an important, but often neglected factor in the mountain water balance. In Central European mountains, the subalpine elevation belt is mostly covered by forests dominated by conifers. In this way, current work contributed to the development of modelling methods in eco-hydrology.

5. REFERENCES

[1] Klaučo M, Gregorová B, Stankov U, Marković V, Lemenkova P (2013) D*etermination of ecological significance based on geostatistical assessment: a case study from the Slovak Natura 2000 protected area*. Central European Journal of Geography 5:28–42. https://doi.org/10.2478/s13533-012-0120-0

[2] Klaučo, M, Gregorová B, Koleda P, Stankov U, Marković V, Lemenkova P (2017) *Land Planning as a Support for Sustainable Development Based on Tourism: A Case Study of Slovak Rural Region*. Environmental Engineering and Management Journal, 16(2):449–458. https://doi.org/10.30638/eemj.2017.045

[3] Lemenkova P (2024) *Artificial Intelligence for Computational Remote Sensing Quantifying Patterns of Land Cover Types around Cheetham Wetlands, Port Phillip Bay, Australia*. Journal of Marine Science and Engineering, 12(8):1279. https://doi.org/10.3390/jmse12081279

[4] Lemenkova P. (2023). *Monitoring Seasonal Fluctuations in Saline Lakes of Tunisia Using Earth Observation Data Processed by GRASS GIS*. Land, 12(11), 1995. https://doi.org/10.3390/land12111995

[5] Wang, Y., Hu, X., Wang, Z., Zhang, Y., Chen, C., Wei, B. (2025). *Interactions of Ecosystem Services and Management Optimization in Complex Hilly Mountainous Environments: A Case Study from Southern China*. Land, 14, 717. https://doi.org/10.3390/land14040717

[6] Lemenkova P. (2022). *Console-Based Mapping of Mongolia Using GMT Cartographic Scripting Toolset for Processing TerraClimate Data*. Geosciences, 12, (3), 140. https://doi.org/10.3390/geosciences12030140

[7] Li, D., Zhang, Y., Gao, Y., Duan, L., Li, H., Zhang, H., Gao, Q., Zhao, M., Liu, Q. (2025). *Coupling Land Use with Multiple Geographical Factors Drives the Evolution of Habitat Quality: Case Study from Resource-Exhausted City—Jiawang District, East China*. Sustainability, 17(7), 2954. https://doi.org/10.3390/su17072954

[8] Al-Huqail, A. A., Islam, Z. (2025). *Ecological Stress Assessment on Vegetation in the Al-Baha Highlands, Saudi Arabia (1991–2023)*. Sustainability, 17(7), 2854. https://doi.org/10.3390/su17072854

[9] Lemenkova P (2025b) *Automation of image processing through ML algorithms of GRASS GIS using embedded Scikit-Learn library of Python*. Examples and Counterexamples, 7:100180. https://doi.org/10.1016/j.exco.2025.100180

[10] Cao, Y., Ye, Z., Bao, Y. (2024). *The Influence of Climate Change and Socioeconomic Transformations on Land Use and NDVI in Ordos, China*. Atmosphere, 15(12), 1489. https://doi.org/10.3390/atmos15121489

[11] Liu, L., Yao, Y., Li, Y., Xie, Z., Ning, J., Yu, R., Fan, J., Kan, Y., Zhang, L., & Xu, J. (2024). *Satellite Evidence for Increasing in Terrestrial Evapotranspiration over the Contiguous United States from 2001 to 2022*. Forests, 15(8), 1472. https://doi.org/10.3390/f15081472

[12] He, X., Xu, T., Bateni, S. M., Neale, C. M. U., Auligne, T., Liu, S., Wang, K., Mao, K., & Yao, Y. (2018). *Evaluation of the Weak Constraint Data Assimilation Approach for Estimating Turbulent Heat Fluxes at Six Sites*. Remote Sensing, 10(12), 1994. https://doi.org/10.3390/rs10121994

[13] Li, S., Nurmemet, I., Seydehmet, J., Lv, X., Aili, Y., Yu, X. (2024). *Spatiotemporal Dynamics and Driving Factors of Soil Salinization: A Case Study of the Yutian Oasis, Xinjiang, China*. Land, 13(11), 1941. https://doi.org/10.3390/land13111941

[14] Lemenkova, P. (2025). *Improving Bimonthly Landscape Monitoring in Morocco, North Africa, by Integrating Machine Learning with GRASS GIS*. Geomatics, 5(1):1-29. https://doi.org/10.3390/geomatics5010005

[15] Roh, M., Lee, S., Jo, H.-W., & Lee, W.-K. (2024). *Development of a Forest Fire Diagnostic Model Based on Machine Learning Techniques*. Forests, 15(7), 1103. https://doi.org/10.3390/f15071103