Evaluation of the hydrological response of a forest small catchment of Lake Patzcuaro, Michoacán

Rivera-Ruiz, Pedro[1,3]; Rubiños-Panta, Juan E.[1*]; Fernández-Reynoso, Demetrio S.[1]; Mendoza-Pérez, Cándido[1]; Prado-Hernández, Jorge V.[2]; Khalil-Gardezi, Abdul[1]; Dehesa-Carrasco, Ulises[3]

[1] Colegio de Postgraduados, Posgrado en Hidrociencias, Campus Montecillo, Texcoco, Estado de México, México, C. P. 56264.
[2] Universidad Autónoma Chapingo, Departamento de Suelos, Carretera México-Texcoco km 38.5, Chapingo, Texcoco, Estado de México, México, C. P. 56230.
[3] Instituto Mexicano de Tecnología del Agua, Progreso, Jiutepec, Morelos, México, C. P. 62550.
* Correspondence: jerpkike@colpos.mx

Citation: Rivera-Ruiz, P., Rubiños-Panta, J. E., Fernández-Reynoso, D. S., Mendoza-Pérez, C., Prado-Hernández, J. V., Khalil-Gardezi, A., & Dehesa-Carrasco, U. (2025). Evaluation of the hydrological response of a forest small catchment of Lake Patzcuaro, Michoacán. *Agro Productividad*. https://doi.org/10.32854/ar11yc97

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Daniel Alejandro Cadena Zamudio

Received: August 13, 2024.
Accepted: May 11, 2025.
Published on-line: July XX, 2025.

Agro Productividad, 18(6). June. 2025. pp: 55-63.

ABSTRACT

Objective: To analyze the hydrological response of the Malacate forest small catchment, based on rainfall and runoff event variables recorded between 2013 and 2016.

Design/Methodology/Approach: Rainfall was recorded with digital rain gauges (0.2 mm accuracy), at a gauging station in the outlet of the small catchment. It was equipped with a long-throat gauger and an ultrasonic sensor. Runoff was recorded every 3 minutes. Linear and multiple regression analysis were used to study 11 characteristic rainfall and runoff variables. The aim was to identify those characteristics that influence the hydrological response of the small catchment.

Results: The highest correlation with surface runoff (R^2=0.7657) was recorded by the following variables: total rainfall of the event (TRE), previous 2-day rainfall (P2DR), rainfall intensity in 30 minutes (RI30), and runoff time (ROT). Meanwhile, the correlation between the measured and estimated runoffs recorded R^2=0.8558 (1:1 ratio). TRE is the most influential variable in the behavior of surface runoff (R^2=0.6706).

Study Limitations/Implications: The role of rainfall variables and their influence in the runoff and hydrological response of the forest small catchment must be subjected to further studies.

Findings/Conclusions: The results allow a first approximation to the hydrological response of a forest small catchment. In conclusion, the hydrological response depends on the moisture level of the small catchment and the characteristics of the rainfall.

Keywords: runoff, rainfall, hydrological response, forest small catchment, regression analysis.

INTRODUCTION

Currently, experimental basins are of interest for hydrological researches. These studies evaluate the effects and changes of soil use, as well as management actions implemented in the catchment. They can also relate and arrange the influence of the different factors

that take part in the hydrological cycle. Hydrological studies are frequently based on experimental basins, where inflow (rainfall) and outflow (water flow) can be quantified. In addition, the effect of different types of plant covers and the relationship between inflows and outflows can be evaluated in experimental basins (García and Gallart, 1997).

Brown *et al.* (2005) and Van Dijk *et al.* (2012) studied the hydrological response to forest change in <100 km^2 basins and provided a deep insight about the impact of forest change of annual runoffs in small catchments. For their part, Beck *et al.* (2013) and Zhang *et al.* (2015) concluded in their researches about small catchments that deforestation, forest exploitation, urbanization, soil cover change, forest fires, and pests can increase annual runoff, while afforestation or the maintenance or improvement of forest covers has a positive impact on the flow of streams.

Other studies about small catchments reported that great variations in the hydrological response to forest change and in forest cover throughout time are a consequence of factors such as forest type, typology, climate, hydrological regimes, soil, geology, and landscape morphology (Zhang and Wei, 2014). In most cases, the inconsistent hydrological responses are just the consequences of the complex processes of basins and the heterogeneity of the landscape, weather, and geology (Stednick, 1996; Vose *et al.*, 2011).

Therefore, the objective of this study was to evaluate the hydrological behavior of the Malacate forest small catchment, to establish the hydrological response to the intensity of rainfall events and to determine factors that provide a better explanation for the runoff response. This study has a double purpose: (i) to provide data about the hydrological functioning of a mountain area where plant cover has not been removed; and (ii) to provide data about a potential future trend of many basins of the Trans-Mexican Volcanic Belt, in order to strengthen the importance of maintaining forest covers in the basins of the mountains in Mexico and all over the world.

MATERIALS AND METHODS

Study area

The Malacate small catchment is located in the basin of Lake Patzcuaro and has an area of 149.24 ha. The soil use is divided as follows: 74.13% forest (pine-oak), 16.64% scrubland, 5.53% areas without plants, 2.51% eroded pasture-forest, and 1.19% rainfed agricultural lands (Figure 1). Small catchment tributaries directly discharge in the lake. It has a 576-m elevation gradient between the watershed (2,651 m) and the gauging station (2,075 m).

Instruments and equipment

The hydrological response of the outflow of a small catchment should be studied through the continuous recording of the runoffs. Hydrographs are developed using water expenditure. They show the constant behavior of water level rises and can be used to report the instant changes of water flow throughout time. These phenomena are the result of the different hydrological processes in the small catchment.

In order to carry out a comparative analysis of the hydrological response of the Malacate small catchment, a temporal scale (per event or water level rise) was used to

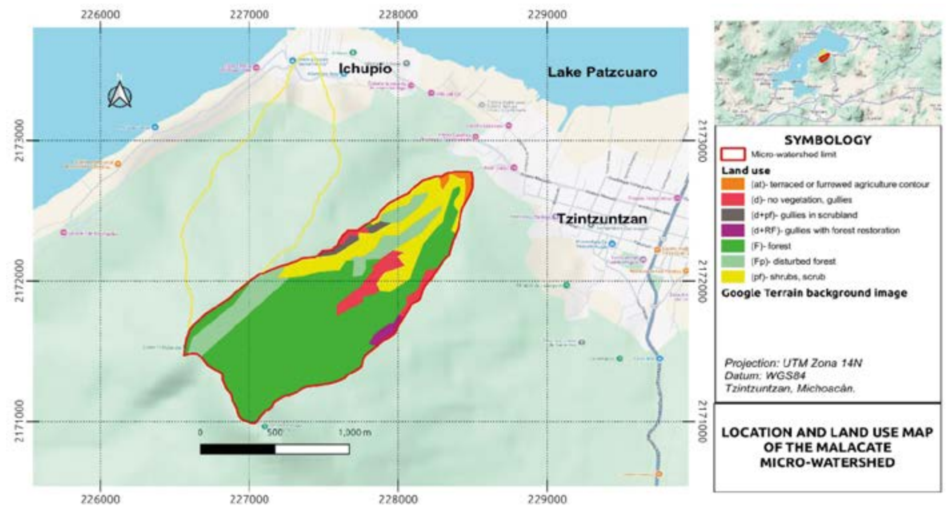

Figure 1. Location and soil use of the Malacate small catchment, Tzintzuntzan, Michoacán.

obtain the most reliable data. Water level rise is usually defined as a sudden increase in the water flow of a riverbed —*i.e.*, it is a response to a high volume of rainfall in a catchment basin (Nadal-Romero *et al.*, 2010). The bed of the Malacate small catchment is intermittent and it only has runoffs during the raining season. Consequently, no base-runoff was recorded.

A gauging station was built in the lower part of the Malacate small catchment to monitor its activity during four years (2013-2016). The following measurement equipment and instruments installed in the small catchment were used to gather data from both the inflow (rainfall) and the outflow (water flow):

1) A HoBo rain gauge with a rocker connected to a data logger to measure rainfall (0.2 mm accuracy).
2) A long-throat gauger (Figure 2a), equipped with an ultrasonic sensor (Figure 2b). This technology was developed by the Instituto Mexicano de Tecnología del Agua (IMTA) and records water level every 3 minutes and measures it as water expenditure.

Figure 2. long-throat gauge (a) and ultrasonic sensor equipment (b) used to record the runoffs.

Variable recording and data analysis

Thirty major superficial runoff events with a maximum water flow were selected to analyze the hydrological response of the small catchment from 2013 to 2016. Events 1-4, 5-9, 10-21, and 22-30 took place in 2013, 2014, 2015, and 2016, respectively. Serrano *et al.* (2005) maintain that a hydrograph by itself is not enough to provide information about the runoffs and the processes that take part in their creation. Consequently, once the 30 events were established, the following variables were analyzed: total rainfall of the event (TRE; mm); previous 2-day rainfall (P2DR; mm); rainfall time (RT; min); rainfall intensity in 30 minutes (RI30; mm/h); runoff (RO; mm); runoff time (ROT; min); maximum runoff (MAXRO; l/s); average runoff (ARO; l/s); runoff response time (ROREST, min), from the beginning of the rainfall to the beginning of the runoff; discharge time (DIST; min), from the end of the rainfall to the end of the runoff; and time to peak runoff (TPRO; min), from the beginning of the rainfall to the peak of the runoff.

A database was developed to create a correlation matrix, in order to determine the relation between the variables. Meanwhile, a multiple regression analysis was conducted to identify and explain the relationship between the different variables and their influence in the hydrological response, as well as to appropriately evaluate the impact of the different parameters. A graphical analysis and the coefficient of determination (R^2) were used for this purpose. These procedures were used to identify which variables have the best correlation to explain their influence on the superficial runoff of the Malacate small catchment. In addition, rainfall events were grouped in three ranges based on the total rainfall of the event, to analyze the average behavior of the variables with higher correlation with the rainfall.

RESULTS AND DISCUSSION

The runoff events recorded during the four-year evaluation were very diverse, ranging from 3.8 to 44.4 mm. Overall, the hydrological response was depended on the rainfall conditions, including the amount of rainfall in previous days. Data from 2 to 5 days before the runoff response were analyzed. The results indicated that the rainfalls of 2 previous days had a better response. This situation is a consequence of the shallow luvisols with clay present in the small catchment.

Figures 3 and 4 show the normalization of the values of the analyzed variables. Each of their values was divided between the maximum value for the 30-event data set, with the following results: 44.4 mm (TRE), 32.2 mm (P2DR), 292.2 min (RT), 86.0 mm/h (RI30), 11.3 mm (RO), 567.0 min (ROT), 2,432.3 l/s (MAXRO), 486.4 l/s (ARO), 141.5 min (ROREST), 464.1 min (DIST), and 159.5 min (TPRO).

The first rains of the rainy season do not usually have a hydrological response, likely because the soil of the small catchment is dry, after several months without rain (November-April). However, relatively intense rains will still cause runoffs.

The year-long relationship between rainfall and runoff is conditioned by constant rainfall events on previous days; therefore, prior moisture in the soil likely plays a major role in the hydrological response of the small catchment. Serrano *et al.* (2005),

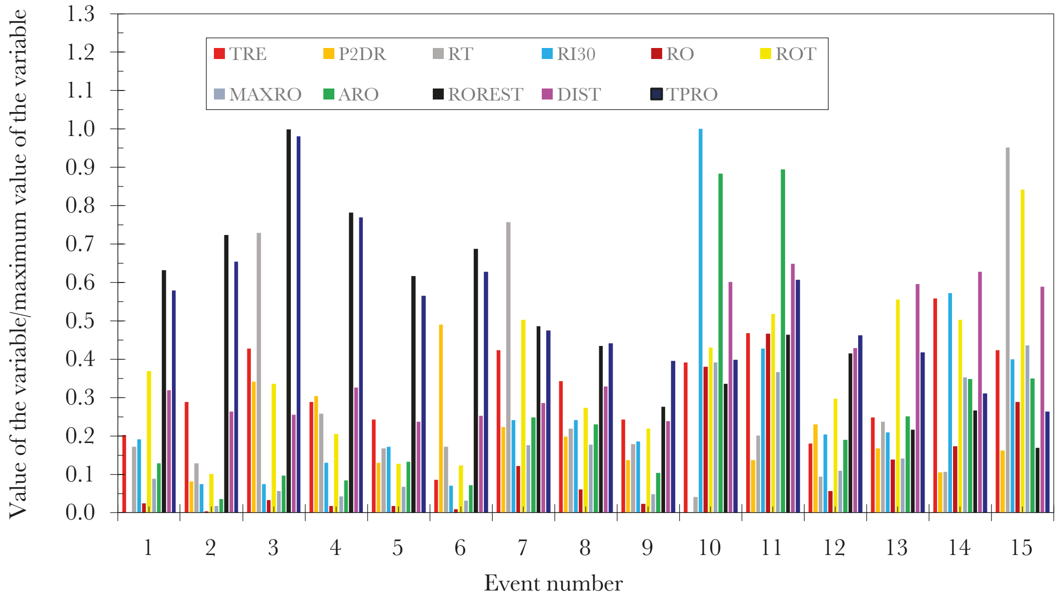

Figure 3. Normalization of the values of the rainfall and runoff characteristics for events 1 to 15.

TRE: total rainfall of the event; P2DR: precipitation for 2-day rainfall; RT: rainfall time; RI30: rainfall intensity in 30 minutes; RO: runoff; ROT: runoff time; MAXRO: maximum runoff; ARO: average runoff; ROREST: runoff response time; DIST: discharge time; TPRO: time to peak runoff.

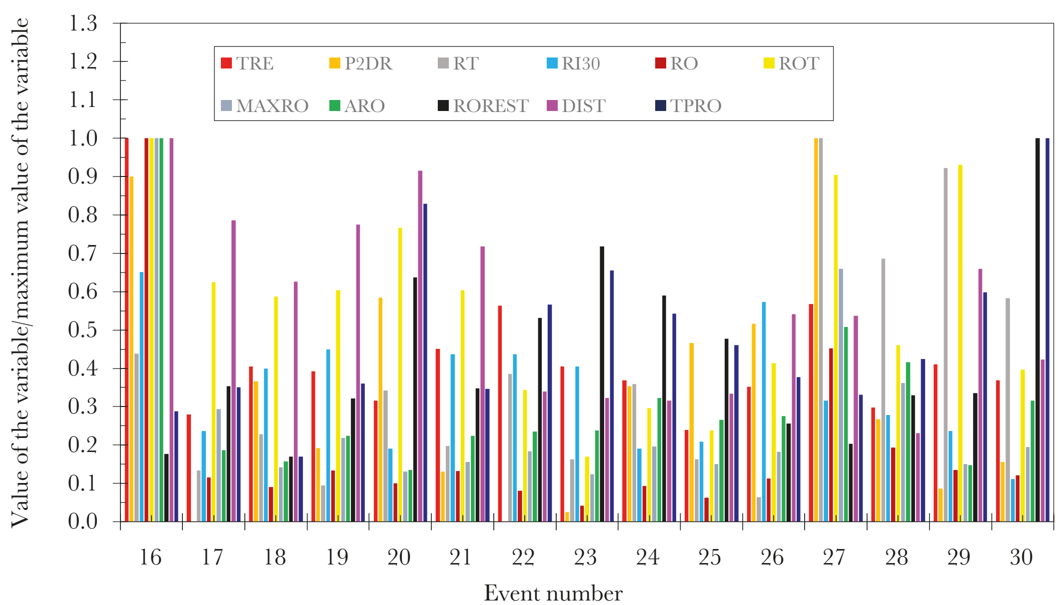

Figure 4. Normalization of the values of the rainfall and runoff characteristics for events 16 to 30.

TRE: total rainfall of the event; P2DR: precipitation for 2-day rainfall; RT: rainfall time; RI30: rainfall intensity in 30 minutes; RO: runoff; ROT: runoff time; MAXRO: maximum runoff; ARO: average runoff; ROREST: runoff response time; DIST: discharge time; TPRO: time to peak runoff.

Nadal-Romero *et al.* (2008), Latron and Gallart (2008), Bart and Hope (2010), and Penna *et al.* (2011) reported similar trends. Additionally, the role of rainfall intensity is fundamental for the hydrological response in the Malacate small catchment, with different intensities and similar rainfall volume, but with different prior moisture conditions, resulting from previous rainfalls (Ares, 2014; Nadal-Romero *et al.*, 2010; Nunes *et al.*, 2011).

Zabaleta *et al.* (2007), Latron and Gallart (2008), Nunes *et al.* (2011), and Yao *et al.* (2021) have reported that even soils with a dry hydrological condition can record greater runoff, as a result of the more intense rainfall.

The results provide an overview of the complex operation of the hydrological response of the small catchment: as rainfall increases, the runoff does not increase, because similar rainfall values can have very different responses. Therefore, in face of a given volume of rainfall in the small catchment, the hydrological response is conditioned by other factors beyond rainfall itself (Boulet *et al.*, 2021; Ares, 2014).

Runoff usually increases as the rainfall volume increases, although the same total rainfall can also quantify different runoffs. Therefore, the response to this variable is conditioned by other factors, including rainfall intensity and rainfall time —which are in turn dependent on the rainfall volume accumulated in previous days. This phenomenon is reflected in the response time before the runoff starts and is recorded at the outflow of the small catchment, as well as in the discharge time and the time to peak runoff.

In the case of the Malacate small catchment, a higher maximum runoff is expected with a more intense rainfall in a 30-minute period (Nu Fang *et al.*, 2011; Yao *et al.*, 2021). Meanwhile, a greater rainfall intensity decreases the response time —*i.e.*, a shorter time elapses between the beginning of the rainfall and the first runoff at the outflow of the small catchment.

Discharge time is defined as the time that elapses from the moment it stops raining to the moment when the runoff ends. Therefore, with a higher maximum runoff, the time it takes for the runoff to exit the small catchment increases. Meanwhile, a greater maximum runoff rate results in a shorter response time before the runoff exits the area.

The multiple regression analysis identified the variables that have the best correlation and weighed up their influence on runoff: total rainfall of the event (TRE), the previous 2-day rainfall (P2DR), rainfall intensity in 30 minutes (RI30), and runoff time (ROT). The resulting equation has a R^2 of 0.7657 and is set forth as:

$$RO = -2.8725 + 0.1376TRE + 0.0727P2DR + 0.0345RI30 + 0.0032ROT$$

where RO, TRE and $P2DR$ are measured in mm, while $RI30$ and ROT are measured in mm/h and min, respectively.

Figure 5 shows the graphical representation of the results from the multiple regression model, including the measurements for the runoff and their estimations (R^2=0.8558; ratio 1:1). Overall, the multiple regression model underestimates the runoff by 14.42%.

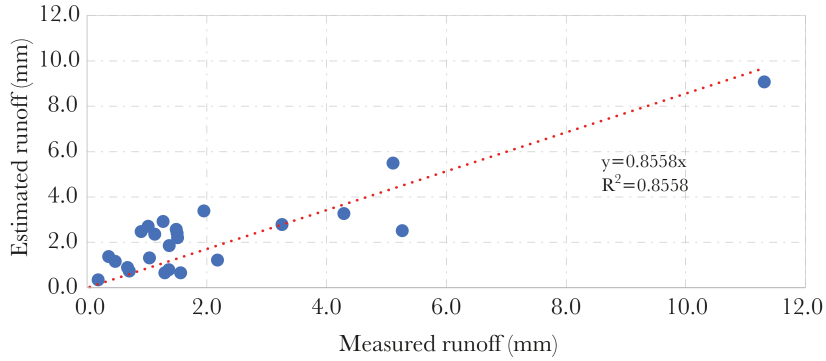

Figure 5. Ratio between the runoff measured and estimated using the multiple regression model on four variables from the Malacate small catchment.

The total rainfall of the event (TRE) by itself is the analyzed variable with the best correlation with the runoff (RO), with an R^2 of 0.6706. When the runoff values are estimated based on a multiple regression analysis, R^2 reaches 0.8608 (Figure 6), proving that the four identified variables are correlated and provide a better explanation of the runoff behavior in the Malacate small catchment. Rodríguez-Blanco *et al.* (2010) and Nu Fang *et al.* (2011) reached similar conclusions. However, just like Nadal-Romero *et al.* (2008), this study concluded that the model is more accurate when it is used to estimate the runoff for >10 mm rainfall events; however, it is inaccurate with lower rainfalls.

Meanwhile, the results were analyzed and the average values for seven variables were correlated with the total rainfall of the event (TRE). Table 3 shows how the events were grouped into three rainfall ranges: 10 to 15 mm, 15 to 20 mm, and 20+ mm.

As the total rainfall of the event (TRE) increases, the following characteristics likewise increase: rainfall intensity in 30 minutes; runoff; maximum and average runoffs; runoff length; and discharge time. Evidently, the runoff response time decreases as rainfall increases.

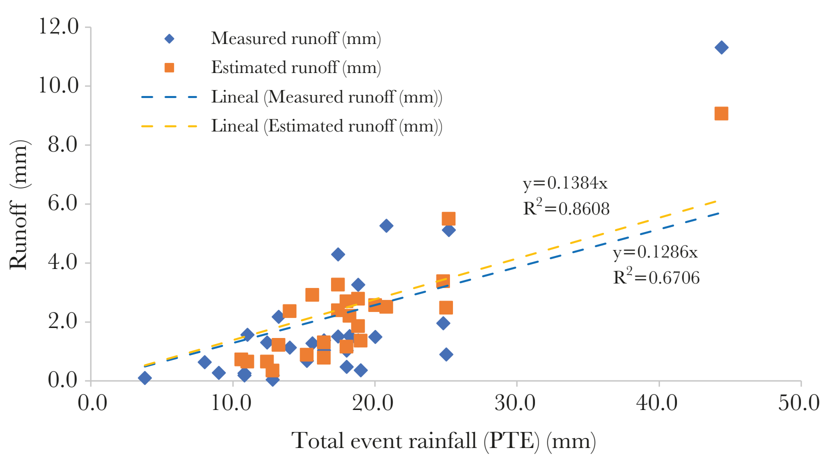

Figure 6. Relation between the measured and estimated runoffs, based on the multiple regression model used to determine the total rainfall of the event in the Malacate small catchment.

Table 3. Average characteristics of the rain and runoff per range of the total rainfall of the events (TRE) recorded from 2013 to 2016 in the Malacate small catchment.

Range of total event rainfall (TRE) (mm)	RI30 (mm/h)	RO (mm)	MAXRO (l/s)	ARO (l/s)	ROT (min)	ROREST (min)	DIST (min)
10 a 15	16.13	0.84	338.47	86.97	207.67	69.33	202.52
15 a 20	31.00	1.52	495.31	141.45	273.08	68.53	221.26
>20	40.73	4.34	1101.51	260.23	366.00	46.92	299.48

RI30: Rainfall intensity in 30 minutes; RO: Runoff; MAXRO: Maximum runoff; ARO: Average runoff; ROT: Runoff time; ROREST: Response time; DIST: Discharge time.

CONCLUSIONS

The data recorded in the Malacate small catchment during four water years have enabled a first approach to its hydrological response and the following conclusions have been reached:

(i) Some rainfall variables play a major role in hydrological response, including the total rainfall of the event, the rainfall of the 2 previous days, and the rainfall intensity in the first 30 minutes.

(ii) In most cases, the catchment can absorb even the most intense rainfall; nevertheless, the higher soil moisture resulting from rains in the previous days will cause surface runoffs —*i.e.*, the hydrological response of the small catchment depends on the previous rainfall, as well as the characteristics of the rainfall.

ACKNOWLEDGMENTS

The authors would like to thank the Instituto Mexicano de Tecnología del Agua for the facilities and opportunities provided for this research and the recording and compilation of data and information about the Malacate forest small catchment, established through internal research projects.

REFERENCES

Ares, M. G. (2014). Lluvia, escurrimiento y producción de sedimentos en una microcuenca agrícola del sistema de Tandilia. Tesis doctoral. Facultad de Ciencias Agrarias y Forestales. Universidad Nacional de la Plata. Argentina. 117 pp. https://doi.org/10.35537/10915/40494

Bart, R. & Hope, A. (2010). Streamflow response to fire in large catchments of a Mediterranean-climate region using paired-catchment experiments. *Journal of Hydrology, 388*(3-4), 370-378. https://doi.org/10.1016/j.jhydrol.2010.05.016

Beck, H.E., Bruijnzeel, L.A., van Dijk, A.I.J.M., McVicar, T.R., Scatena, F.N., Schellekens, J. (2013). The impact of forest regeneration on streamflow in 12 mesoscale humid tropical catchments. *Hydrology and Earth System Sciences*. 17, 2613-2635. https://doi.org/10.5194/hess-17-2613-2013

Boulet, A.-K.; Rial-Rivas, M.E.; Ferreira, C.; Coelho, C.O.A.; Kalantari, Z.; Keizer, J.J.; Ferreira, A.J.D. (2021). Hydrological processes in eucalypt and pine forested headwater catchments within mediterranean region. *Water, 13*(10), 1418. https://doi.org/10.3390/w13101418

Brown, A.E., Zhang, L., McMahon, T.A., Western, A.W., Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology, 310*(1-4), 28-61. https://doi.org/10.1016/j.jhydrol.2004.12.010

García, R. J.M. & Gallart, F. (1997). Las cuencas experimentales como base para el estudio de la erosión y la desertificación. En: Ibáñez, J.J., Valero, B. & Machado, C. (Eds.), El paisaje mediterráneo a través del espacio y del tiempo. Implicaciones en la desertificación. Geoforma Ediciones. 221-238.

Latron, J., & Gallart, F. (2008). Runoff generation processes in a small Mediterranean research catchment (Vallcebre, Eastern Pyrenees). *Journal of Hydrology, 358*(3-4), 206-220. https://doi.org/10.1016/j.jhydrol.2008.06.014

Nadal-Romero, E., Latron, J., Lana-Renault, N., Serrano-Muela, P., Martí-Bono, C. & Regües, D. (2008). Temporal variability in hydrological response within a small catchment with badland areas, central Pyrenees. *Hydrological Sciences Journal, 53*(3), 629-639, https://doi.org/10.1623/hysj.53.3.629

Nadal-Romero, E, Regües, D. & Serrano-Muela, P. (2010). Respuesta hidrológica en una pequeña cuenca experimental pirenaica con dos ambientes extremos: cárcavas y bosque de repoblación. *Pirineos. Revista de Ecología de Montaña*, 165, 135-155. https://doi.org/10.3989/Pirineos.2010.165007

Nu Fang, F., S. Zhi-Hua, L. Lu & J. Cheng. (2011). Rainfall, runoff, and suspended sediment delivery relationships in a small agricultural watershed of the Three Gorges area, China. *Geomorphology, 135*(1-2), 158-166. https://doi.org/10.1016/j.geomorph.2011.08.013

Nunes, N. A., de Almeida, C. A., Coelho, O. A. C. (2011). Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Applied Geography, 31*(2), 687-699. https://doi.org/10.1016/j.apgeog.2010.12.006

Penna, D., Tromp-van Meerveld, H. J., Gobbi, A., Borga, M., and Dalla Fontana, G. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. *Hydrology and Earth System Sciences, 15*(3), 689-702, https://doi.org/10.5194/hess-15-689-2011

Rodríguez-Blanco, M.L., M.M. Taboada-Castro & M.T. Taboada-Castro. (2010). Factors controlling hydro-sedimentary response during runoff events in a rural catchment in the humid Spanish zone. *Catena, 82*(3), 206-217. https://doi.org/10.1016/j.catena.2010.06.007

Serrano, M. M. O., Regües, D., Latron, J., Martí, N. C., Lana-Renault, N. y Nadal, R. E. (2005). Respuesta hidrológica de una cuenca forestal en la montaña media pirenaica: el caso de San Salvador. *Cuaderno de Investigación Geográfica*, 31, 59-76. Universidad de La Rioja. https://dialnet.unirioja.es/servlet/articulo?codigo=1975902

Stednick, J.D. (1996). Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology, 176*(1-4), 79-95. https://doi.org/10.1016/0022-1694(95)02780-7

Van Dijk, A.I.J.M., Peña-Arancibia, J.L., Bruijnzeel, L.A. (2012). Land cover and water yield: inference problems when comparing catchments with mixed land cover. *Hydrology and Earth System Sciences, 16*(9), 3461-3473. https://doi.org/10.5194/hess-16-3461-2012

Vose, J.M., Sun, G., Ford, C.R., Bredemeier, M., Otsuki, K., Wei, X., Zhang, Z., Zhang, L. (2011). Forest ecohydrological research in the 21st century: what are the critical needs? *Ecohydrology, 4*(2), 146-158. https://doi.org/10.1002/eco.193

Yao Y, Dai Q, Gao R, Gan Y, Yi X. (2021). Effects of rainfall intensity on runoff and nutrient loss of gently sloping farmland in a karst area of SW China. *PLoS ONE, 16*(3): e0246505. https://doi.org/10.1371/journal.pone.0246505

Zabaleta, A., M. Martínez, Uriarte, J.A. & I. Antigüedad. (2007). Factors controlling suspended sediment yield during runoff events in small headwater catchments of the Basque Country. *Catena, 71*(1), 179-190. https://doi.org/10.1016/j.catena.2006.06.007

Zhang M. & Wei X. (2014), Contrasted hydrological responses to forest harvesting in two large neighbouring watersheds in snow hydrology dominant environment: implications for forest management and future forest hydrology studies. *Hydrological Processes*, 28, 6183-6195. https://doi.org/10.1002/hyp.10107

Zhang, X.K., Fan, J.H., Cheng, G.W. (2015). Modelling the effects of land-use change on runoff and sediment yield in the Weicheng River watershed, Southwest China. *Journal of Mountain Science, 12*(2), 434-445. https://doi.org/10.1007/s11629-013-2762-x