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Hydrological Processes in a Small Research Watershed under Forest Coverage in the Coast of Chiapas, Mexico

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Abstract

In the hydrological watershed, some natural processes take place in which the interaction of water, soil, climate and vegetation favors the capture of water. The present study aimed to evaluate preliminary information regarding the hydrological response and the water balance in a small research watershed with tropical forest cover (15˚01'44"N and 92˚13'55"W, 471 m, 2.3 has). Events of precipitation, direct runoff, infiltration rate and baseflow were performed. The amount, duration and intensity of rainfall events were recorded with the use of a pluviograph. Surface runoff was quantified with an established gauging station, an H-type gauging device and a horizontal mechanical gauging limnograph. Runoff base flow was measured at the gauging station using the volume-time method. Infiltration was measured using a triple ring infiltrometer, taking two measurements in the upper part and two in the lower part of the microbasin. Evapotranspiration was measured with the amount of rainfall entering and runoff leaving the watershed. In the study period, annual rainfall of 4417.6 mm distributed over 181 events were recorded; about 70% of the storms showed lower intensities at 20 $mm{\cdot}h^{-1}$. The total runoff was 345.8 mm caused by half of the rainfall events, which represents 7.8% of the total rain; 77% of runoff events showed lower sheets of 5 mm and an average specific rate of 20.7 $L{\cdot}s^{-1}{\cdot}ha^{-1}$ with a maximum of 113.6 $L{\cdot}s^{-1}{\cdot}ha^{-1}$. Three runoff events were greater than 20.1 mm and caused the 22.5% of the total runoff depth in the study period showing the equilibrium conditions in the hydrological response of the forest. Water outputs like baseflow was 669.5 mm. In this way, 90% of the rainfall is infiltrated every year in the micro-watershed, which shows the importance of the plant cover in the hydrological regulation and the groundwater recharge.

Keywords

Hydrological Response, Tropical Forest, Runoff-Rain Ratio, Water Balance, Groundwater Recharge

1. Introduction

Climate change is affecting hydrological cycles at the watershed level, which impacts some weather parameters such as precipitation, air temperature and humidity, and runoff (Gebrechorkos et al., 2019). The above leads to the need to make decisions related to watershed water resources planning (Mehan et al., 2016).

The effects of vegetation change on hydrological processes in watersheds have been studied (Siad et al., 2019; Lai et al., 2020). Proof of this is that several studies have aimed to assess vegetation cover changes on runoff and sediment production by considering aspects such as the trend of vegetation change and its driving mechanism (Zhang et al., 2019).

Vegetation and the hydrological cycle are interconnected (Gerten et al., 2004). The condition of development of the vegetation, natural or planted and its management, exert a determining influence on the hydrological conditions of a watershed.

This hydrological and landscape relationship exerts significant control over water movement in drainage basins and flow response through various reciprocal relationships (Todd et al., 2006; Valencia-Leguizamón & Tobón, 2017). Therefore, when the forest component has been eliminated, changes in water yield, response to runoff, and sediment yield in a tropical watershed are expected.

In the coastal watershed of Chiapas's State, southeast of Mexico, there is enough evidence of the advance of the agricultural border and the pressure on the existing forest resources. Particularly in the Sierra Madre Region, there are large areas totally deforested; where once there were forests, now there are fields with annual crops, soils used against their natural aptitude, land with bare soil or in the worst case, gullies and torrents whose presence in the field indicates the advanced stage of lands degradation.

These changes in land use endanger the hydrological-environmental balance not only at the local level but also at the regional level (Bruijnzeel, 2004; Kusumastuti et al., 2007), since interactions occur within the watershed (water-soil-plant-precipitation) and interrelations between the upper part and the middle and lower parts of it, so it is possible to deduce the possible externalities that have occurred in these territorial spaces (García & Gallart, 1997). However, there are currently few studies that analyze the determinant role of vegetation and land uses on the hydrology of watershed in the Costa and Sierra Madre Region located in Chiapas, Mexico.

The pioneering and unique study at the same time in this field of research in the tropical region of Chiapas, is the project executed for thirteen years by several research and teaching institutions supported by the National Water Commission. Of this project, the first in southeastern Mexico, some publications have been derived specifically in the Huehuetán river watershed (Baumann et al., 2002; CONAGUA, 2011; Rodríguez & Arellano, 2006). As part of these studies, this paper shows results on the water balance of a small-scale forest watershed with data derived from this project.

Under this consideration, in this study an experimental small watershed was used with the purpose of measuring the hydrological conditions under forest coverage and the role of the vegetation component on the hydrological response, the relationship between the water inlets and outflows (runoff coefficient) at watershed level in the lower middle part of the Coatán river watershed, in Chiapas, Mexico.

2. Materials and Methods

2.1. Biophysical Description of Study Site

The research was carried in a micro watershed located in the municipality of Tapachula in the region called Soconusco, in the State of Chiapas, Mexico and is located between 15˚01'44" North latitude and 92˚13'55" of west longitude, to an average height of 471 m above the sea level in the Vega de los Gatos farm. The study area is located in a landscape of hills of the Coatán watershed, belonging to Hydrological Region No 23, also known as the Costa de Chiapas (Figure 1).

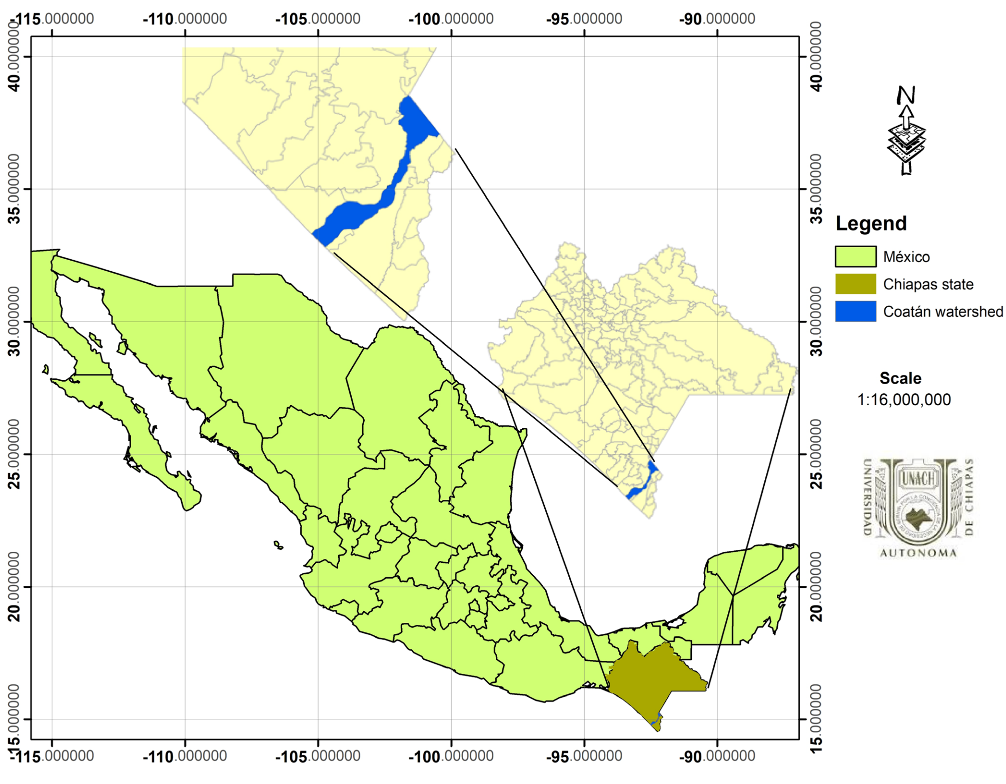

Figure 1. Location of area of study.

Climate type is Am (w), that corresponds to the warm humid with rains and dry days in summer. The average annual temperature is 26˚C, April being the hottest month with 37˚C and January is the warmest month with 15˚C. The average annual rainfall is 4618 mm. The land within the micro watershed of study is constituted geologically by lands of the Cenozoic, quaternary with sedimentary rocks.

Topography is very irregular with steep slopes of up to 45%. The soil type within the micro watershed is humic Acrisol; the texture of the soil varies within the micro-watershed of sandy loam to clayey clay (CONAGUA, 2011). The watershed area is 2.3 hectares; it has a vegetal cover that consists mainly of evergreen rainforests.

2.2. Measurement Instruments and Evaluation Methods

2.2.1. Rain Records

Rain was recorded using a Hellman pluviograph (**Figure 2(a)**). From each pluviogram generated is possible to obtain information about the start and end of the event rain, amount in milimeters (mm), duration (minutes) and intensity (mm per hour).

2.2.2. Surface Runoff

The surface runoff was quantified by using a gauging station composed of: a control section with defined dimensions (1.7 m wide, 1 m high and 5 m long); an H type flume gauge (normal one foot high) and a horizontal mechanical flume limnigraph Rossbach type Stevens F-95, multiple resolution of record and scale 1:5 (**Figure 2(b)**).

2.2.3. Flow Measurement

In the gauging station the runoff base flow was measured every two days with the volume and time method in the discharge of the flume installed at the outlet of the study watershed (**Figure 2(c)**).

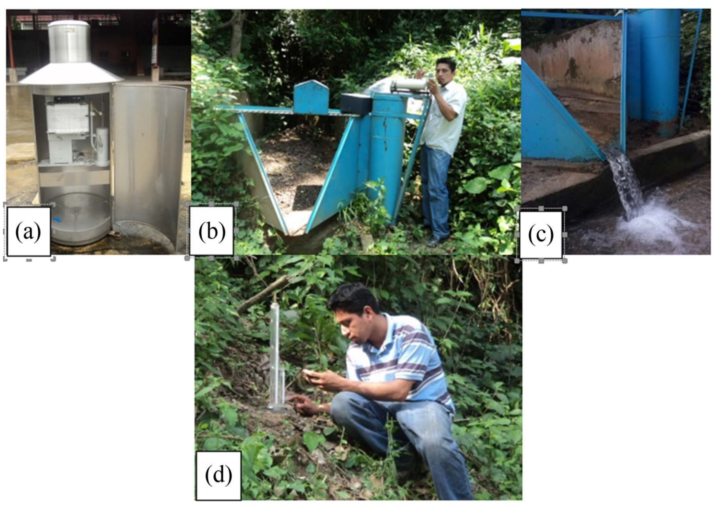

Figure 2. The experimental small watershed located in Chiapas, Mexico.

$$Q = V/t$$

where:

Q = Runoff base flow in liter per seconds (L/s)

V = Water volume collected in liter (L)

t = Time to collect a water volume in seconds (s)

2.2.4. Infiltration

Infiltration was measured by using the Triple Ring Infiltrometer Measure System (Figure 2(d)). Four infiltration measurements were carried out; two in the upper part and two in the lower part of the micro watershed.

2.2.5. Evapotranspiration

Evapotranspiration was deducted from inputs (such as rain) and output (as runoff) of the watershed, applying the following formula:

$$ET = P - Q$$

where:

ET = Evapotranspiration in mm

P = Precipitation in mm

Q = Runoff in mm

2.3. Data Collection and Analysis

The information recorded for each of the variables was expressed graphically and in tabular form. Six class intervals were defined for the analysis of the amount of rainfall and its frequency expressed as a percentage (0.1 to 20 mm, 20.1 to 40 mm, 40.1 to 60 mm, 60.1 to 80 mm, 80.1 to 100 mm and >100 mm). The maximum specific runoff recorded was analyzed over a period of six months by taking readings that were compared with respect to the runoff or flow rate. Finally, a comparison of means was made between the values obtained for rain, surface runoff, base flow and evapotranspiration during the months of evaluation.

3. Results and Discussions

In the period from April to November the total rainfall was of 4417.6 mm, it was distributed in 181 rain events. July was the rainiest month with 874.5 mm, an amount that represents 20% of the total in the period. Near 60% of the events rain recorded were smaller than 20 mm (Figure 3).

Figure 3 shows the frequency histogram of rainfall recorded in the study period where it is observed that the curve is skewed to the left, with a high value of the Kurtosis coefficient (3.8) which indicates the magnitude of the crest in which about 60% of the rain events presented sheets less than 20 mm. In the same way, it was obtained that only 11% of all the events presented sheets superior to 60 mm. There were six events that exceeded 100 precipitated sheet; the largest of these was 146 mm occurred during June. In this sense it is worth mentioning that in most of the state territory there is a general rainy season from May to

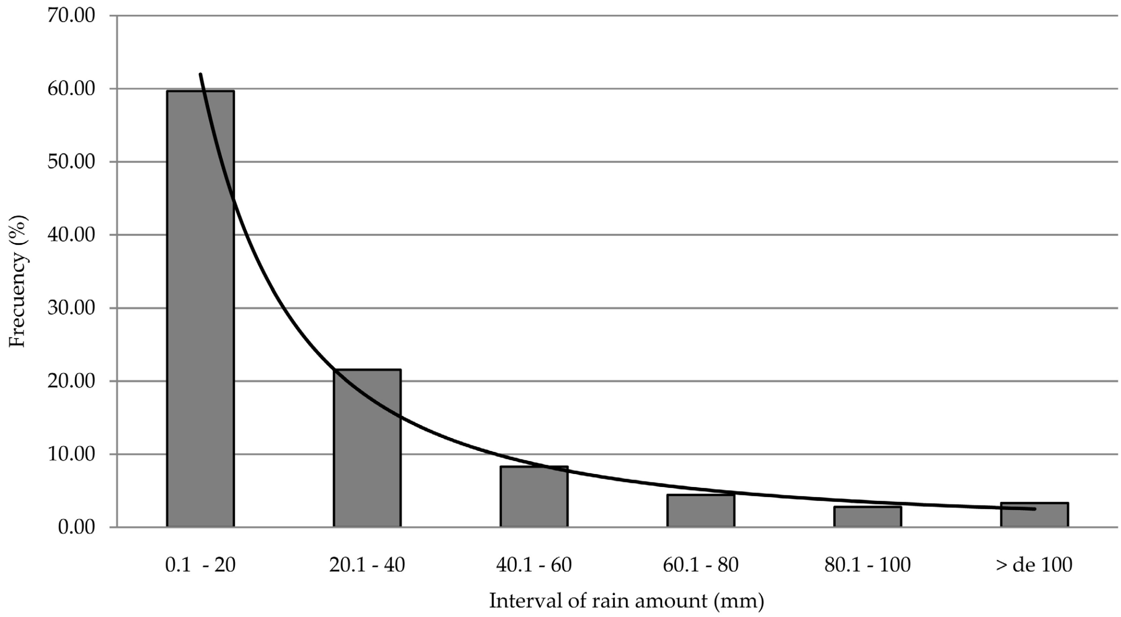

Figure 3. Rain amount and its frequency in study small watershed, Chiapas, Mexico.

October, called summer rain. In the month of May there are irregular and scattered rains, corresponding to a period of transition that ends the dry season and the start of the rainy season. In the middle of July, a small dry interval known as a mid-summer drought or canicule occurs.

It is important to note that according to the historical records of rainfall on the study area, there was a decrease of 10.7% in the amount of rainfall with respect to the annual average value. According to various studies there is a negative trend in the amount of annual precipitation (Kusumastuti et al., 2007; CONAGUA, 2011). These conclusions come from analyzing long series of daily records of accumulated rainfall (period 1945-1994) for an average of climatological stations located along the Chiapas state. The decrease in average annual rainfall can be associated with two natural conditions: the variation of very long-period climate (decades), and regional climate changes (PACCCH, 2011).

In the same way, Schroth et al. (2015), point out that, that due to climate change, in the Coffee Zone of the Sierra Madre de Chiapas an average rainfall reduction of 80 to 85 mm is expected in the three reference altitudes zones: low (from 500 to 1000 meters above sea level); medium zones (from 1000 to 1500 meters above sea level) and high zones (from 1500 to 2000 meters above sea level).

It is important to emphasize that in Mexico the distribution of rain depends on its annual average value, as well as its distribution throughout the year. The distribution is measured through the average number of days with rainfall per year. In this sense it is necessary to note that in the Costa de Chiapas region there are an average of 120 days with rain during the year (Breña & Jacobo, 2006). Strictly, 176 rainy days were presented in the study micro-watershed, a value well above the average value reported in the literature.

On the other hand, it is important to mention that the rains present fluctuations from one year to the next. These changes are forms of climate variability. This variation in the rain regime may cause, occasionally, into serious damages for users and activities dependent on water resources such as agriculture, livestock, health, etc. (Magaña & Méndez, 2002); it can also cause catastrophes in natural ecosystems and human settlements.

From the point of view of climate in our region, days with precipitation are greater (rainy days). Other regions of the Mexican Republic whose average number of rainy days is 120 (rainy areas) are: The Meseta Central de Chiapas, the Sierra Madre de Oaxaca, the Gulf of Mexico coast, the Sierra Madre Oriental and on the eastern slopes of the Cordillera Neovolcanica (Breña & Jacobo, 2006). This determines that the Costa de Chiapas region is a high rainfall area.

Regarding the rain intensity values of the recorded rainfall events, close to 70% of the events presented intensity less than 20 $mm \cdot h^{-1}$. Only 5% of the total presented intensity values above 60.1 $mm \cdot h^{-1}$; this percentage was represented by 9 storms. Only one event of rain showed an average intensity of 120 $mm \cdot h^{-1}$ and was recorded during September with a total sheet of 128.4 mm.

It is important to point out that, the predominance of low intensities is characteristic of the type of orographic precipitation, which is produced by the shock of humid air masses against mountain barriers, which in the study area is represented by the Sierra Madre, whose maximum height is 4100 m (at the Volcán Tacaná).

The intensities of storms decrease with the increase in storm duration. Further, a storm of any given duration will have a larger intensity if its return period is large. In other words, for a storm of given duration, storms of higher intensity in that duration are rarer than storms of smaller intensity (Subramanya, 2003).

It is well known that the rainfall intensity directly influences two aspects that determine the hydrological response of a watershed: on the average volume of precipitation that forms runoff, and on the direct runoff (Breña & Jacobo, 2006). It is that part of runoff which enters the stream immediately after the precipitation. It includes surface runoff, prompt interflow and precipitation on the channel surface (Subramanya, 2003). In addition, it is important to note that the amount of rain precipitated on a watershed directly influences the runoff in it (Breña & Jacobo, 2006).

On the other hand, Bruijnzeel (2004) emphasizes that the shorter and more intense the rains, the influence exerted by forests on the regulation of flows will decrease. However, the removal of forest cover can cause a fast flow and increase the risk of flooding during the rainy season and the reduction of perennial streams during the dry season.

In terms of maximum value of specific runoff of this study, it was 113.5 $L \cdot s^{-1} \cdot ha^{-1}$, with an average value of 20.68 $L \cdot s^{-1} \cdot ha^{-1}$. Likewise, it is necessary to point out that only 29.5% of the events exceeded the average value, that is, only 26 of the 88 events presented values above 20.6 $L \cdot s^{-1} \cdot ha^{-1}$ (**Figure 4**).

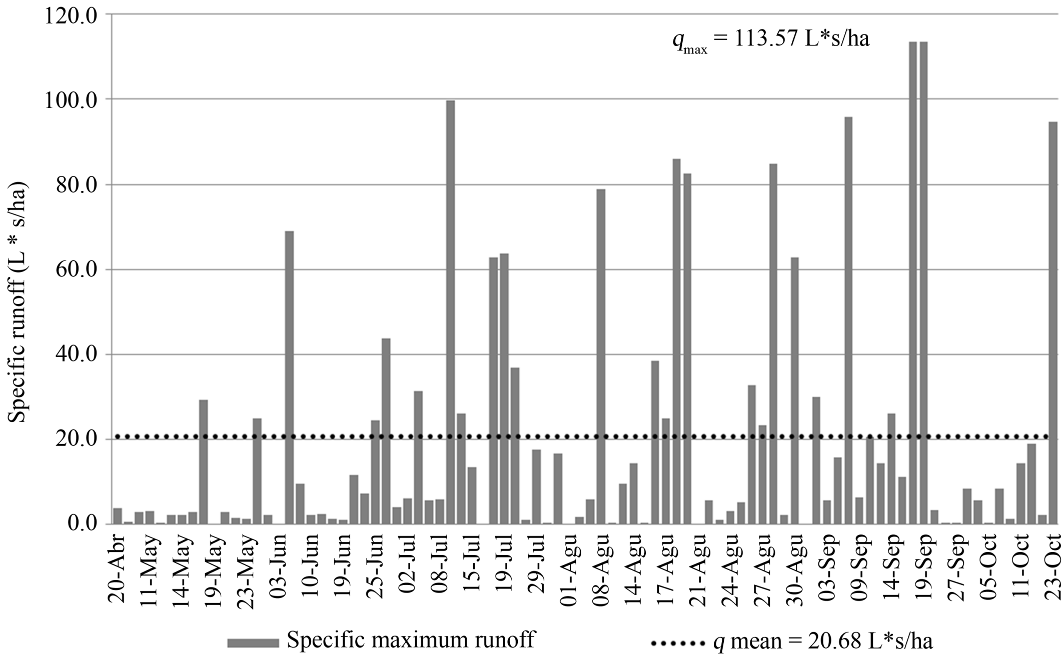

Figure 4. Specific maximum runoff recorded in a forest micro watershed in Chiapas, Mexico.

In terms of infiltration, it was found that in the upper part of the watershed, the basic infiltration is 2.0 mm·h^{-1} and the average infiltration results in 40.5 mm·h^{-1}; while in the lower part the average infiltration value is reduced to 24.4 mm·h^{-1} and the basic infiltration remains at 1.9 mm·h^{-1}. These hydrological conditions of the soil explain in part the behavior of the watershed to the response of surface runoff, since it is notorious that while the upper part of the watershed allows a greater infiltration of rainwater; it is the middle and lower part of the micro-watershed that provides the most runoff at the outlet, and the one that presents a high response to rain events. Thus, during a storm it is expected that by decreasing the infiltration and as the soil becomes saturated with moisture (wet fronts), the flows on the ground will originate causing direct runoff.

It should be mentioned that the infiltration process is a very complex phenomenon and depends on many factors, among which the temporal distribution of rainfall, its quantity and intensity, physical properties of the soil, geographical and orographic characteristics of the land (slope), moisture content, physical and chemical properties of water, among others (Breña & Jacobo, 2006; Baumann et al., 2008; Nadal et al., 2010).

On the other hand, the minimum and maximum values of the runoff coefficient in the study period varied between 0.0003 and 0.2068 respectively; obtaining an average value for the watershed of 0.0735. This result indicates that the runoff generation was very low despite the high rainfall regime and slopes conditions. It means that the local conditions of vegetation and soil type are decisive in the hydrological behavior of the study watershed (Baumann et al., 2008; CONAGUA, 2011).

Table 1. Hydrological processes in a forest micro watershed in Chiapas, Mexico.

Month	Rain (mm)	Runoff (mm)	Base flow (mm)	Evapotranspiration (mm)
April	226	5.51	0.00	220.49
May	559.1	16.45	0.00	542.65
June	620.5	57.95	23.95	538.6
July	874.5	87.07	154.32	633.11
August	793.3	79.32	152.92	561.06
September	832	76.41	206.1	549.49
October	487.6	23.06	131.34	333.2
November	24.6	0.00	0.85	23.75
Total (mm)	**4417.6**	**345.77**	**669.48**	**3402.35**
% respect to total rain	**100**	**7.83**	**15.15**	**77.02**

In a comparison of the rainfall-runoff curve from a farm microcatchment (steep slope 50%) with the curve from another microcatchment (steep slope 10%), Baumann et al. (2008) revealed that rainstorms up to approximately 70 mm generate more runoff on moderate slopes (10%) with heavy clay soils, than on steep slopes with a sandy clay loam texture. It can be that soil depth and the percolation and drainage conditions in the subsoil are important controlling factors of runoff response (Kusumastuti et al., 2007). The results of evapotranspiration calculated monthly are presented in Table 1.

The values of evapotranspiration deduced from the rainfall-runoff relationships for the watershed only give an idea of order of magnitude relative to the flow of water in the forest ecosystem but they are within the values reported in the international literature on the subject.

4. Conclusion

Despite the high rainfall in the study period, 90% of the rainfall is infiltrated in the micro-watershed and runoff is quite low (7%) which shows the importance of the plant cover in the hydrological regulation of the tropical watersheds and the high groundwater recharge. The results give a specific idea about the hydrological behavior of forest ecosystems in the areas of the Sierra Madre de Chiapas. Finally, it is worth mentioning that watershed instrumentation provides very valuable and basic information for sustainable water resource management. However, due to its nature, this type of work requires good economic support for the acquisition of hydrometeorological measurement equipment, its installation, calibration, operation, maintenance and surveillance, as well as technical training for both field measurements and the analysis and interpretation of the data measured in the experimental basins.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. Lastly, all other issues such as plagiarism, falsification of data, misconduct, and others were duly observed by the authors.

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