A saturated excess runoff pedo-transfer function for vegetated watersheds

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ABSTRACT

Since Hewlett and Hibbert's publication on small watershed hydrology in 1967, there has been a slow recognition that saturated excess runoff is the main runoff mechanisms in vegetated watersheds. While most pedo-transfer functions for predicting runoff are based on infiltration excess runoff, few are based on saturation excess runoff. We, therefore, developed a simple pedo-transfer function. The function was tested in eight watersheds distributed over three continents that differ in climate, size, topographic relief and land use. Six watersheds were used to develop the pedo-transfer function. The watershed response to rainfall was very similar. In each catchment, a threshold amount of rainfall needed to be exceeded before direct runoff (consisting of both surface runoff and interflow) would occur. After the threshold was exceeded, direct storm runoff was linearly related to rainfall depth indicating that a nearly constant proportion of the watershed was the source area for direct runoff. The source areas were small for watersheds with deep soils. Threshold was strongly dependent on the initial moisture conditions. In the remaining two watersheds, we predicted the water level each of the terminal lakes for a 30 year period using the saturation excess pedo-transfer function where the rainfall threshold was computed using the Thornthwaite-Mather procedure and the baseflow from remaining watershed employing a linear reservoir model. Taking the simplicity of the prediction technique with only four calibrated parameters into account, the lake levels were predicted well including the rise in the lake level in the last ten years when the climate became wetter.

1. INTRODUCTION

There is a long history of avoiding flood disasters by methods to predict and prevent floods. The Egyptians had already developed a flood warning system (i.e., runners) and directed excess flood water in Lake Moeris in the Faiyum hollow, so Alexandria would not flood (Garbrecht, 1987). More than 43 centuries later, there are still 250 refereed articles in scientific journals that have been published in the last year on "flood prediction" according Science Citation Index. This is understandable since information for predicting floods and the capacity to calculate complex problems has increased at least a billion fold, making it possible to refine the historic techniques for predicting discharge at the outlet of a watershed and develop new ways to predict the locations of overland flow in the watershed. Opinions on the "right" complexity vary among hydrologists and soil scientists with developers of SHE and SWAT (Abbott et al., 1986; Arnold et al., 1998; Easton et al., 2008) adding more complexity to their already complex models. On the other hand Jakeman and Hornberger (1993) argued that typical rainfall-runoff patterns only contained enough information to constrain simple hydrological models with as little as four free parameters. Zehe and Sivapalan (2009) have furthermore reasoned that due to the spatial heterogeneity and process complexity of the subsurface flow, predicting threshold behaviour requires, as a first step, identification of first order controls.

It is fair to say that the current trend is to develop increasingly more intricate distributed watershed models to represent the complex and heterogenic landscape features (Weiler and McDonnell, 2007). These distributed models are generally based on some form of Darcy's law (Beven, 1985; Beven, 2000) and can predict realistic distributed moisture contents and fluxes when the input data are accurate. Satellite imagery can provide the detail needed for surface features, but precise data for subsurface features are not (yet) available. In addition, averaging of parameters at the watershed scale becomes problematic (McGuire et al., 2005). For example, the detail of a small valley might be lost by increasing grid sizes (Kuo et al., 1999; Weiler and Naef, 2003). Therefore, despite the mathematical rigor that Darcy's law brings, the predictive validity of the models is often in doubt (Seibert, 2003) and several hydrologists, therefore, have moved from fully distributed deterministic models towards more conceptually based models with fewer parameters, describing only dominant hydrological processes at the hillslope and catchment scales (Naef et al., 2002; Wagener et al., 2007). Therefore, we believe that there is still a need for models (i.e., pedo-transfer functions) using few parameters and representing the right "landscape processes". These may look very different from the form based on "small scale physics" (i.e., Darcy's law, Kirchner, 2006).

Many previous attempts to develop pedo-transfer functions for direct runoff such as those developed by Green and Ampt (1911), Horton (1940), Kostiakov, and the rational formula Kuichling (1889) have been based on the relative magnitude of the rainfall intensity and infiltration capacity which is a function of land use and soil type. Since systematically predicting rainfall intensity is almost impossible, and more importantly the rainfall intensity is greater than the saturated conductivity of the soils in well vegetated areas, these methods perform less than satisfactorily (Hewlett and Hibbert, 1967; Schneiderman et al., 2007). It might be of interest here that Horton (1940) perceptual model of infiltration processes was far more sophisticated and complete than normally presented in hydrological texts today (Beven, 2004,a,b,c). Conversely, there are very few pedo-transfer functions that use the saturated excess knowingly. For example the SCS equation is in principle a saturated excess overland flow model (Steenhuis et al. 1995) and has proven in some cases to perform well (Lyon et al., 2004)

In this paper, we are concerned with developing direct runoff pedo-transfer functions for vegetated watersheds in which gravity (and not the water pressure potential) is the dominant force moving the water. These are watersheds with a slope of at least 1 to 2% and vegetation present with saturation excess being the dominant runoff mechanism. The storm runoff is characterized by quick responses to rainfall pulses (Whipkey, 1966; Tesař et al., 2004).

Since pedo-transfer functions are derived statistically, they might not apply outside the area for which they were developed. To make the transfer function widely applicable we will test its validity for several locations throughout the world with different climates and landforms and for which we know the watershed characteristics well enough that we can check its validity. In this paper, we will employ the outflow measurement of a plot and a small watershed in the mountains of the Czech Republic (mild, temperate mixed ocean-continental climate), test it with previously published data for three watersheds in the Ethiopian Highlands (with a semi humid monsoon climate) and for a cloud forest catchment in Honduras. At the end we will combine the transfer function with a water balance to calculate thresholds and predict lake level fluctuation for terminal lakes in Haiti and the Dominican Republic characterized by a semi-arid monsoon climate

PEDO-TRANSFER FUNCTION FOR DIRECT RUNOFF

In the saturation excess pedo-transfer function, direct runoff consisting of fast interflow and surface runoff is generated by rainfall falling on areas that are saturated above the hardpan. The saturated regions expand as the rainstorm progresses (Hewlett and Hibbert, 1967) and the amount of runoff per unit increment of precipitation increases with time (Steenhuis et al, 1995; Liu et al., 2005) after which it becomes constant as we will show in this paper. As expected and shown by sprinkler experiments (Zehe *et al.* 2007) runoff is highly dependent on the initial soil moisture state as a result of the threshold dynamics of the system. Various explanations have been given for these phenomena such as threshold behavior (McGrath et al., 2007; Spence, 2007: Lehmann et al, 2007 and Tromp-van Meerveld and McDonnell, 2006). Essentially, thresholding is a consequence of the highly nonlinear unsaturated hydraulic conductivity curve where the conductivity remains small until it reaches field capacity and enough large pores are filled with water that the landscape starts responding to the precipitation. Based on this, the proposed transfer function for predicting runoff is based on the following main assumptions:

1. Infiltration rates of soils are greater than the rainfall intensity most of the times. We consider areas that are impermeable have been saturated immediately
2. The amount of soil water that can be stored to reach field capacity determines the threshold response to the rainfall. This storage depends on the depth of the restrictive layer and/or the ground water table depth. Watersheds with little storage are fast responding while those with large storage capacities are slow responding and release water over an extended time period
3. Storm runoff response can be fast interflow and/or direct surface runoff. Since the importance of the shallow subsurface flow to the runoff-forming process in headwater catchments between runoff events has been well documented by many investigators at times when the rainfall is equal or larger than the evaporation (i.e., Whipkey 1966, Hewlett and Hibbert 1967, Weyman, 1973; Bonell, 1998; Nieber, 2006), we propose that interflow between rainfall events sets up typical moisture content patterns in the watershed. (Schneiderman et al. 2007; Dahlke et al., 2012).

Thus, in essence we assume that in its most basic form, the landscape after sufficient rainfall (exceeding the threshold) always behaves the same (i.e., is self-organizing) in that direct runoff is generated from a portion of the watershed that is saturated and that is invariant from one storm runoff event to the next. Rainfall in the remaining part of the watershed infiltrates and will either evaporate or become baseflow.

2. MATERIALS AND METHODS

Eight different watersheds in five countries are considered: the Czech Republic, highlands in Ethiopia, Honduras, the Dominican Republic, and Haiti with climates ranging from humid to semi-arid and from monsoon climates to temperate humid climates

Uhlířská Catchment, Czech Republic: Runoff processes are analyzed in the 1.78 km^2 Uhlířská catchment, situated in a mild, temperate mixed ocean-continental climate in the Jizera Mountains in the Czech Republic with peaks of just above 1100 m. The average annual rainfall total is 1400 mm. The Uhlířská catchment consists of approximately 10% valley areas with histosols that can potentially saturate and 90% hillslope areas and its discharge is measured at two scales: the catchment scale (1.78 km^2) and experimental plot scale (0.2 ha). For the experimental plot that is located in a typical hillslope area, the interflow is collected in a trench. No surface flow is observed. The contributing area formed above the trench is about 200 m^2. Its extent varies slightly, according to the degree of saturation of the soil profile (Šanda and Císlerová, 2009; Hrnčíř et al., 2010). The gauging station at the catchment outlet consists of both interflow from the hillsides and saturation excess runoff from the histosols in the watershed.

Forty four rainfall-runoff episodes were selected from eleven vegetation seasons (May – October) between 1998 and 2008 meeting the following criteria. The stream flow at the beginning and the end of each rainfall-runoff episode was at, or very close to the long-term baseflow and consequently, the episodes are clearly bounded in the hydrograph. A minimum recorded rainfall total of 20 mm was chosen as a benchmark for a significant episode. Intense rainfall pulses often follow prolonged periods of shorter, less intense pulses sometimes separated by periods without rain. In order to prevent the contribution of the previous less intense episode to the runoff, some of the selected rainfall-runoff episodes comprise several rainfall pulses, separated by hiatuses of variable lengths.

Ethiopian catchments: Experimental catchments Anjeni, Andit Tid, and Maybar are located within Amhara Regional State, Ethiopia at elevations ranging from 2,200 to 2,500 m. Average annual rainfall for the three sites varies between 1350 and 1500 mm. The catchments are agricultural lands, with extensive soil erosion control structures built to assist the rainfed subsistence farming, but they differ in size, topographic relief, and climate. Andit Tid, the largest study site (4 km^2) and is also the highest and least populated. Hillslopes are very steep and degraded resulting in 54% of the long-term precipitation becoming runoff. Anjeni, located in one of the country's most productive agricultural areas, is the lowest in elevation and highest in population density. The site receives more rain than the other two and has only one rainy season, typically May to October. The slopes are gentle in Anjeni, the soil profile is deep with better infiltration capacity and, most importantly, the catchment is well treated by physical soil and water conservation measures. Finally, Maybar behaves in a similar manner to Anjeni except for the difference in rain season pattern that is bimodal. The majority of information about the Ethiopian catchments comes from two key publications (Liu et al., 2008, Steenhuis et al., 2009) and consequently further information may be found there or requested from the authors.

Honduras: Discharge was measured in 635 ha of a catchment dominated by cloud forests in 4 sub-watersheds located within the La Tigra National Park of central Honduras. Watershed relief is dominated by moderate to steep slopes, with mean slopes ranging from 20 to 30 percent. Elevation ranges from 1374 to 2270 m. The climate is a semi-arid monsoonal climate and is characterized by distinct wet and dry phases. Most of the rain occurs within two wet seasons. Ninety percent of the annual precipitation falls in the wet phase beginning in the end of May and continuing through October. May and October are the peak months for rainfall (Caballero et al., 2013). Long-term climate data recorded at Zamorano University (35 km from the watersheds and at 800 m elevation) indicates a long term average precipitation of 1100 mm. More information can be found in the dissertation of Cabellero et al. (2012)

Haiti and the Dominican Republic: The two locations are Lake Suamatre in Haiti and Lake Enriquillo in the Dominican Republic. The lakes are only about 5 km apart at their closest point and have similar hydrogeological properties (Figure S1a in the supplementary material). Both lakes are terminal lakes with no surface outflow and as determined by satellite based bathymetric mapping using the Reflectance Ratio, have been increasing for the past 10 years (Figure S1b, Romero-Luna and Poteau, 2011) causing flooding of roads, cities, and agricultural land. Deforestation and climate change have been mentioned as the cause for the increase. Lake Saumatre in Haiti is about 120 km^2 with a watershed of 320 km^2. The plain around the lake is composed of alluvium washed down from the neighboring mountains and easily drains water during rain events (Woodring et al., 1924). The mountains border the north and south of the watershed area are composed of limestone. Rainwater also infiltrates easily and flow through the porous media of these limestone areas (Woodring et al., 1924). Lake Enriquillo in the Dominican Republic is 265 km^2 large, its watershed encompasses about 2730 km^2 and lies about 45 m below sea level, making it the lowest point in the Caribbean (Buck et al., 2005). Its salinity level also varies between 2 to 3 times that of nearby ocean water. Remote sensing was used to study the land cover for the years of 1986 and 2010. It was found that, although there has been some land cover change, the change has not been significant enough to influence major changes in the hydrological balance. These two watersheds are used to test the pedo-transfer function. We will combine the transfer function developed for the watersheds in the Czech Republic, Ethiopia, and Honduras with a water balance procedure to calculate the threshold and a linear reservoir to calculate the baseflow routine.

3. RESULTS

We will first demonstrate that saturation excess runoff is the dominant runoff mechanism by showing that the infiltration capacity is generally greater than the rainfall intensity. Subsequently, we will establish that after the threshold value is exceeded, there is a unique and linear relationship between total runoff and total effective precipitation for each rainfall event. Finally we will use (and validate) the transfer function to predict the lake level in Honduras and the Dominican Republic.

Infiltration capacity in the soil

The transfer function is based on the assumption that the infiltration capacity of the soil at the surface is greater than the rainfall intensity. This is contrary to the soil survey data where most soils have hydraulic conductivities smaller than the rainfall intensities. For example a silty loam or finer have conductivities of less than 4 cm h^{-1} (Clapp and Hornberger, 1978). These soil types when measured in the field have conductivities that are in the order of 10 times greater (Merwin et al.1994) and his case for a clay loam exceeded 1 hour 100 year rainfall event. Similar or greater values have been reported in Oregon (Johnson. and Beschta, 1978) and in Honduras (Mendoza et al., 2002) with exception of severely degraded soils (Hanson et al., 2004). In Ethiopia (Bayabil et al, 2010), medium infiltration values are exceeded by rainfall intensities in the order of 5% per year. In the Czech Uhlířská Catchment, mean steady state infiltration rates are 15 m day^{-1} with the coefficient of variation is 126% Tachecí, 2002).

Field infiltration measurements are more meaningful in predicting watershed behavior than the lab derived measurements because lab measurements are made on soils that have been dried, sieved, and repacked. In the field with sufficient organic matter, infiltration rates are higher because aggregates and preferential flow patterns are common. Moreover, when rainfall intensity exceeds infiltration capacity during short periods most of the runoff infiltrates on the way down to the stream when the intensity decreases (Stomph et al., 1992)

Threshold behavior

In order to examine the threshold behavior we have plotted the total discharge vs. total storm precipitation for the watersheds.

Uhlířská Catchment: At the outlet of the 178 ha Uhlířská watershed there is a unique relationship for the 44 runoff events between total precipitation and total runoff that is statistically significant at the 95% confidence level (thin black line in Figure 1). The dashed lines are the 95% confidence intervals. Closer examination of the data indicates that there is a difference in runoff response that is dependent on the initial moisture content of the watershed. When the watershed was nearly saturated (black squares, average initial saturation 0.92) the fitted red line by eye through the outer points shows that the intercept with the precipitation was in the order of 10 mm and when the watershed was dry (asterisks, blue line average initial saturation 0.65) the threshold was just below 60 mm before any runoff was recorded. It is noteworthy that the slope of the two lines is the same and nearly all other runoff rainfall pairs fall between these two outer lines. Once the threshold is exceeded, approximately 80% of the rainfall becomes interflow and direct runoff. The fate of the remaining 20% is discussed later.

The 0.2 ha plot that was located on the hillside does not have any bottom land and for that reason overland flow does not occur and only interflow is measured in the trench (Figure 2). Although there is distinctly greater variation in rainfall and interflow relationship, interflow increases with total storm rainfall. The black line represents the relation of total storm runoff and precipitation and explains 93% of the variation. The dashed lines are the 95% confidence intervals. Similar to the larger watershed, when the profile was wet, the threshold was lower for than when the watershed was dry. The red line is approximately the outer boundary of the black squares and represents the interflow depth when the average watershed saturation was 0.92. The threshold rainfall before interflow occurs is approximately 35 mm. For the next wetness class (average saturation 0.85; grey diamonds) the threshold was in the order of 75 mm (green line). There is one outlier that is not considered. Rainfall amounts for 12 of the rains were too small to exceed the threshold value and thus produced interflow. Examination of Figure 2 shows that the runoff was approximately the precipitation minus the threshold. It should not be a surprise since the watershed of the trench was chosen such that it only contained the contributing area of the collection ditch. The greater threshold value for small experimental plot on the hillside could be partially caused by the fact that the soils have become saturated, before outflow in the trench could occur.

Andit Tid, Anjeni and Maybar in Ethiopia: For Ethiopia we have reported before on the rainfall runoff distribution for Maybar, Anjeni (each approximately 1 km^2) and the 4 times larger Andit Tid watershed (Liu et al., 2008). Since it is difficult in a monsoon climate to mark individual rainfall events, we choose 14 day intervals for characterizing the rainfall runoff relationships. Moreover, since we cannot ignore the evaporation over this period we plot the runoff as a function of effective precipitation which is the total rainfall in a 14 day period minus the potential evaporation during this period. In this monsoon climate for the first 100 mm of rainfall after the dry season hardly any runoff occurs (Liu et al., 2008; not shown). The rainfall runoff ratio increases when more rainfall occurs until after 500 mm effective precipitation during which the rainfall runoff ratio did not change anymore. In Figure 3, we summarize the results for the three watersheds for rainfall runoff pairs after more than 500 mm effective rain since the start of the rainy monsoon over approximately a 10 year team span. In Andit Tid, approximately 56% of late season effective rainfall became runoff, while Anjeni and Maybar where 48% and 50%, respectively. The linear regression for effective precipitation and discharge over a 14 day period has an R^2 = 0.80, indicating a very good for the linear relationship. Even when we regress the three watershed together the fit has still an R2 = 0.61 (Figure 3) The threshold value of 500 mm for the Ethiopian watersheds is much larger than for both the Czech watershed and as we will see next the Honduran watershed because the long dry monsoon phase dries out the soils to the wilting point to an extended depth. The 500 mm cumulative effective precipitation represents a moisture content increase of 0.20 $cm^3\,cm^{-3}$ over 2.-2.5 m of soil from near wilting point to field capacity.

Honduras: For the cloud forest in Honduras we found similarly that there is a strong linear correlation (R^2 = 0.89) between precipitation and direct runoff generation, especially for precipitation events greater than 20 mm hr^{-1} and after the catchment's soils have gone through an initial period of wetting (Figure 4). The slope of regression line was 0.20 in Figure 4 indicating that 20 % of the area is hydrologically active and contributes interflow and direct runoff to the outlet for large storms. These results, although coming from a limited number of rainfall events, indicate a similar behavior to that found in the study of the four small catchments discussed above. The direct runoff source area is small, because due to the generally deep soils only a small portion of the watershed saturates and a large portion of the rainfall becomes baseflow. The threshold of 3 mm is small here, because this watershed is located in a cloud forest that keeps the soil permanently wet.

4. DISCUSSION

Based on the results of six watersheds on three continents, we can formulate a simple transfer function for direct runoff (i.e., both interflow and direct runoff). There is linear relationship between runoff and total rainfall after the threshold is satisfied. The threshold depends on the initial moisture content and is small when the watershed is wet and much larger when the watershed is dry. In addition, the linear relationship can be interpreted as the area that contributes to direct runoff. Thus the moisture content distribution is invariant in time once the threshold is met and independent of initial moisture content. Both the constant area and the linear relationship between total precipitation and total direct runoff is caused by rainfall on hydrologically active areas becoming direct runoff and infiltrating in the remaining part of the watershed the water (Steenhuis et al. 1995)

In addition, we find that the deeper the soils the smaller the direct runoff source areas. The Czech watershed is underlain by a hardpan and nearly 80% of the rainfall becomes runoff. The remaining 20% flows through the fractured bedrock and drains into the aquifer forming the long term baseflow (Šanda et al., 2006, 2009). The Ethiopian watersheds are intermediate and the Honduran watershed is the deepest and has the smallest area contributing to direct runoff. This should not be surprising since it is well known that deep watersheds have baseflow throughout the year and therefore from mass balance considerations, the direct runoff has to be relatively small.

5. APPLICATION/VALIDATION

Lakes Saumatre and Enriquillo (Fig. S1 in the supplementary material) are hydrologically closed basin lakes and therefore the lake level is determined by difference between the evaporation from the lake and the inputs to the lake consisting of precipitation on the lake and the direct runoff and baseflow into the lake.

To calculate the watershed contributions to the lake we will use the saturated excess pedo-transfer function discussed above and calculate the threshold T as the

$$T = S_{max} - S$$

where S_{max} is the maximum storage in the root zone and S is the actual storage calculated with the Thornthwaite-Mather Procedure (Thornthwaite and Mather, 1955; Steenhuis and van der Molen, 1986). The hydrologically active source area for direct runoff and the maximum storage are calibrated. The “recharge source area” is the remaining part of the watershed where excess rainfall above the maximum storage is recharged to a linear ground water reservoir. The half-life of the linear reservoir is calibrated. Other input consists of rainfall and potential evaporation on the watershed. Thus to determine the lake level only four parameters are calibrated: direct runoff source area, maximum storage of the source areas for direct runoff and recharge and the half-life of the linear groundwater reservoir

The lake elevations in Figures 5a and 5b are plotted in terms of change from the lowest level. For Lake Saumatre, a lake level of zero is plotted for 1998, the year of the lowest lake surface area. Elevations in Lake Saumatre varied within a range of about 1.5 m from 1985 to 2002 (Fig. 5a). After 2003, Lake Saumatre had a rapid rise of about 5 m in water levels over just 8 years. The lowest surface area for Lake Enriquillo occurs in 2003. Before 2003, Lake Enriquillo varied within a range of about 4.5 m from 1982 to 2002. Within 7 years after 2003, Lake Enriquillo made a rapid rise of about 6.5 m (Figure 5b)

The parameter values used for the simulation, are shown in Table 1, Figures S2a and S2b in the supplementary material, display the main water inputs and outputs including direct rainfall, evaporation, and watershed inputs for the lakes. The parameter values in Table 1 were manually adjusted until a good fit was obtained. To create this fit, maximum storage capacities in the lower range of the values from USAID survey (Romero Luna and Poteau, 2011) were used in the Dominican lake Saumatre water balance. Thirty per cent of the watershed contributed to direct source runoff and the remaining recharged to the groundwater reservoir with a half-life of 10 days. The Haitian watershed's soils were more degraded than in the Dominican Republic and had therefore very low maximum storage capacities in all areas of the watershed. It is assumed that 55% of the watershed area quickly generates direct runoff from rain events with a maximum soil storage capacity of 25 mm. Part of this water is delivered via underground passaged in the lime stone (Table 1). The watershed input was a combined value of the runoff and base flow from the watershed. Surface runoff accounted for 60% of the water from the catchment and subsurface flow accounted for 40% of the flow (Figure S2a and S2b).

Figures 5a and 5b show simulated lake levels overlaid by the yearly elevation change. The result of the simulation with pedo-transfer function illustrates rainfall exceeding a threshold in terms of soil capacity in 2003. In the last 7 to 8 years, there has been an increase in months of high precipitation leading to greater watershed inputs to the lake when excess water after soil saturation began to surpass evaporative losses. Increases in water followed the increase in storage of the lakes (Fig. 5). In 2009, calculated water inputs generated from the watershed began to level off. As shown in Figure 5, the monthly water balance simulation moderately fits the elevation changes. The pattern of relatively constant lake levels up to 2003 and a rise afterwards, is simulated correctly especially for Lake Enriquillo where both simulation and observation stated a rise at the same time. The water level rise for Lake Saumatre began only in 2005 while the simulation had the lake level start rising in 2003 similar to Lake Enriquillo. The cause of the difference in lake level rise is likely because our subsurface representation is too simplistic. There must be also a threshold value for groundwater for Lake Saumatre that needs to be exceeded before it starts contributing flow. In summary, the lake levels are well simulated taking into account that the underlying mechanism is a pedo-transfer function with only 4 parameters for fitting.

6. CONCLUSIONS

The approach of the study was designed to capture a central physical process and describe the direct runoff dynamics empirically without being overly prescriptive concerning the physical details that govern that process at smaller scales. This is in accordance with Kirchner (2006) who argues that in order to solve everyday water management problems the development of universal practical predictive tools for real-time operational purposes is required.

The conclusion that each site regardless of the location, climate and topography eventually reaches a threshold point where runoff response can be predicted by a linear relationship with effective precipitation has a potential for practical implications. This means that the source area for direct runoff and interflow is nearly constant after the rainfall exceeds the threshold. We found that the contributing source area was smaller for watershed with deeps soils than watersheds underlain by a restricting layer. Furthermore, the threshold values increased with decreasing initial moisture contents.

The present research may contribute to the solution of the problem of how to conceptualize and parameterize the effects of the antecedent conditions in a catchment on runoff formation (Weiler and McDonnell, 2007). However, it needs to be emphasized the present saturated excess pedo-transfer function should be tested further under what condition it does not apply.

7. ACKNOWLEDGEMENTS

This research has been supported by the Czech Technical University in Prague (SGS10/OHK1/2T/11), Czech Science Grant Agency 205/09/0831, the Czech Ministry of Education, Czech Republic (CEZ MSM 6840770002) and the Czech Ministry of Environment (SP/2e7/229/07), USAID through and HED grant, LASPAU (Academic and Professional Programs for the Americas), Cornell University that provided matching funds, and an anonymous donor.

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LIST OF TABLES AND FIGURES

Table 1. Parameters Used in Saturated Excess Pedo-transfer Calculations for the two watersheds in Haiti and the Dominican Republic.

	Saumatre		Enriquillo	
	Area (Portion)	Storage (S_{max}) [mm]	Area (Portion)	Storage (S_{max}) [mm]
Hydrological active direct runoff	0.3	40	0.55	25
Hillside – Recharge Area	0.7	150	0.45	70
Aquifer Half-life	10 days		10 days	

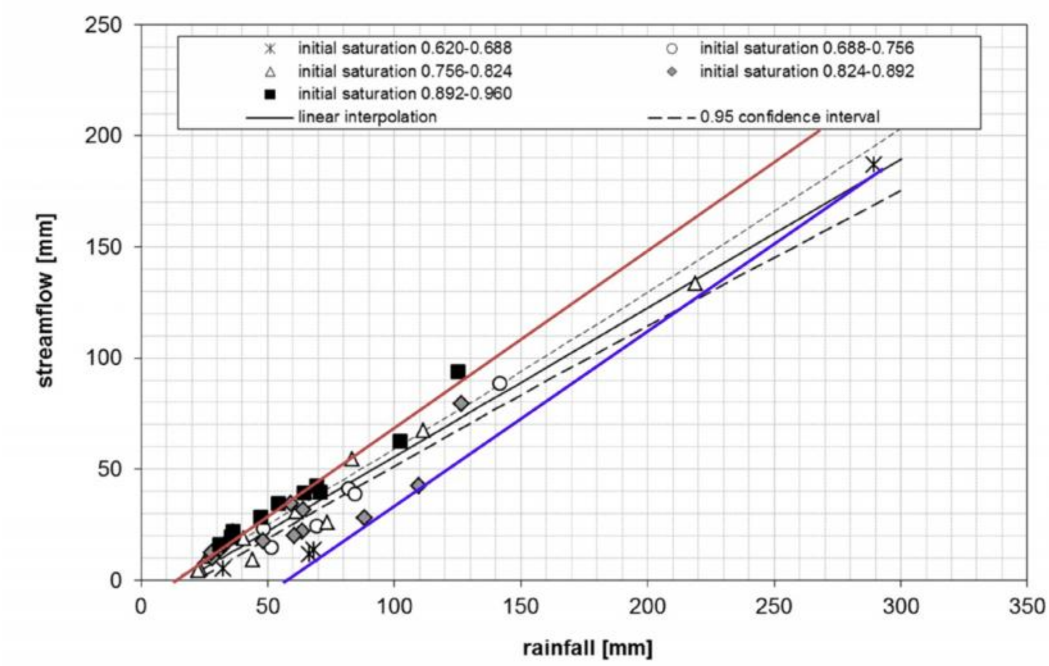


Figure 1: Relationship of total precipitation and total runoff at various initial water saturation contents (symbols) at the the outlet of the 178 ha Uhlířská watershed. The black line is the fitted linear regression with 95% confidence intervals indicated with the dashed lines. The red and the blue line**s** bound the rainfall runoff events**.**

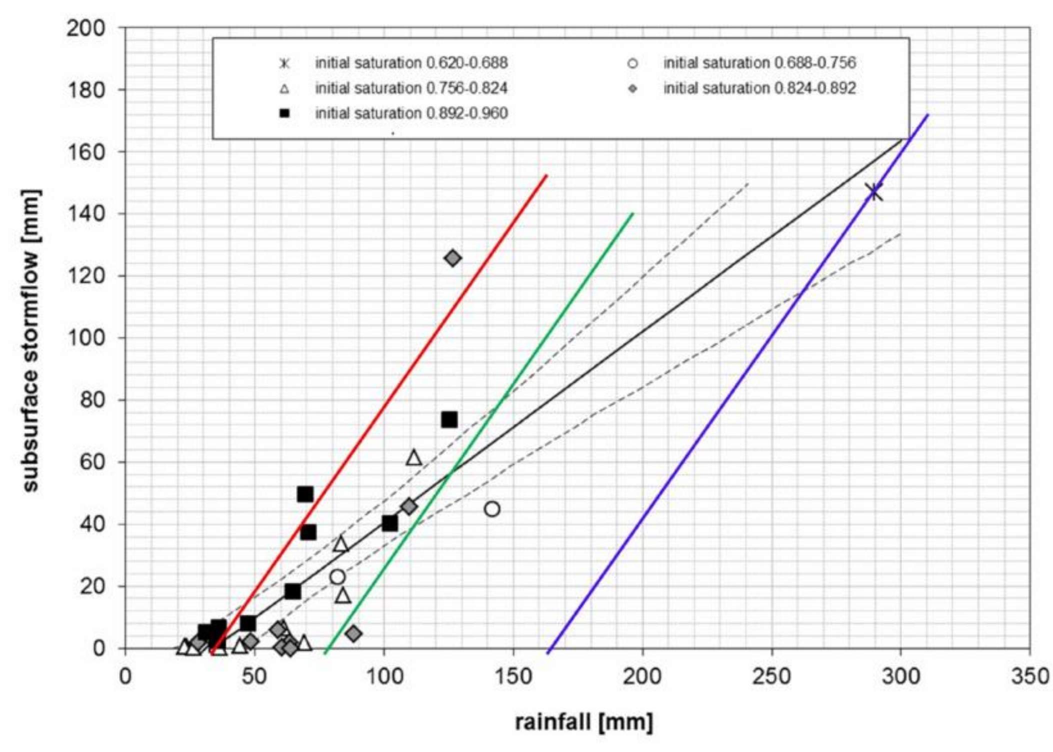


Figure 2: Relationship of total precipitation and total interflow at various initial water saturation contents (symbols) in the subsurface trench for the experimental 0.2 ha plot. The black line is the fitted linear regression with 95% confidence interval

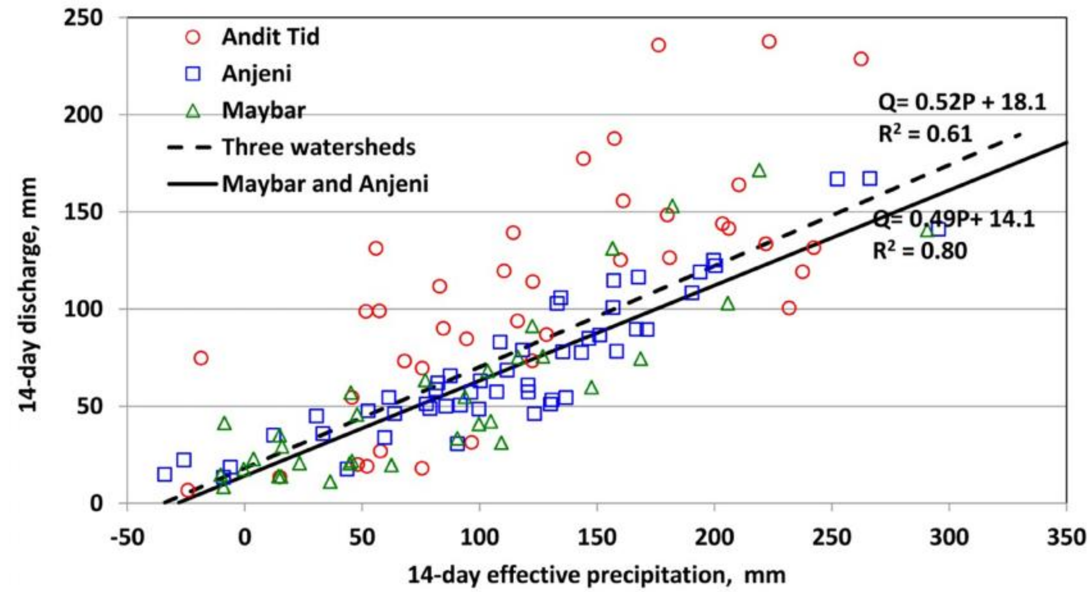


Figure 3: Biweekly summed rainfall/discharge relationships for Andit Tid, Anjeni and Maybar when the sum of precipition minus potential evaporation (effective precipitation) exceeds 500 mm since the start of the rainy monsoon phase.

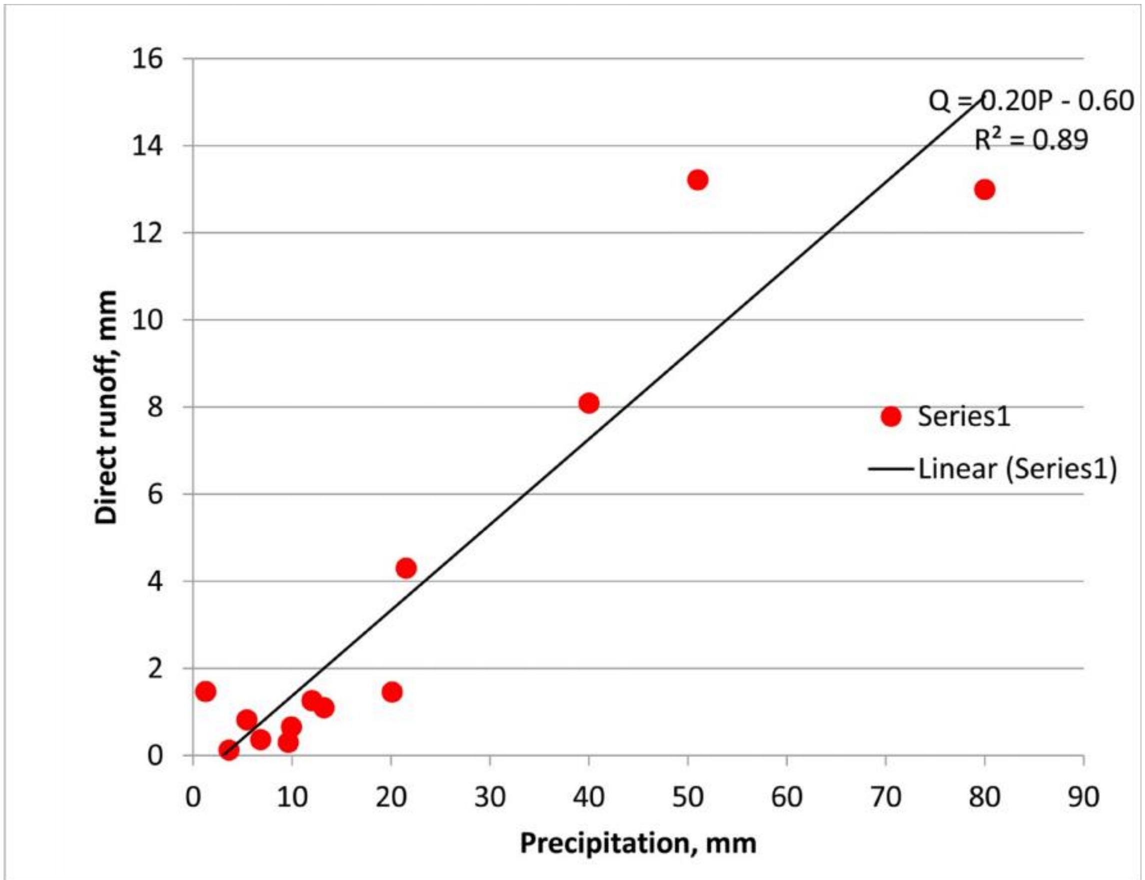
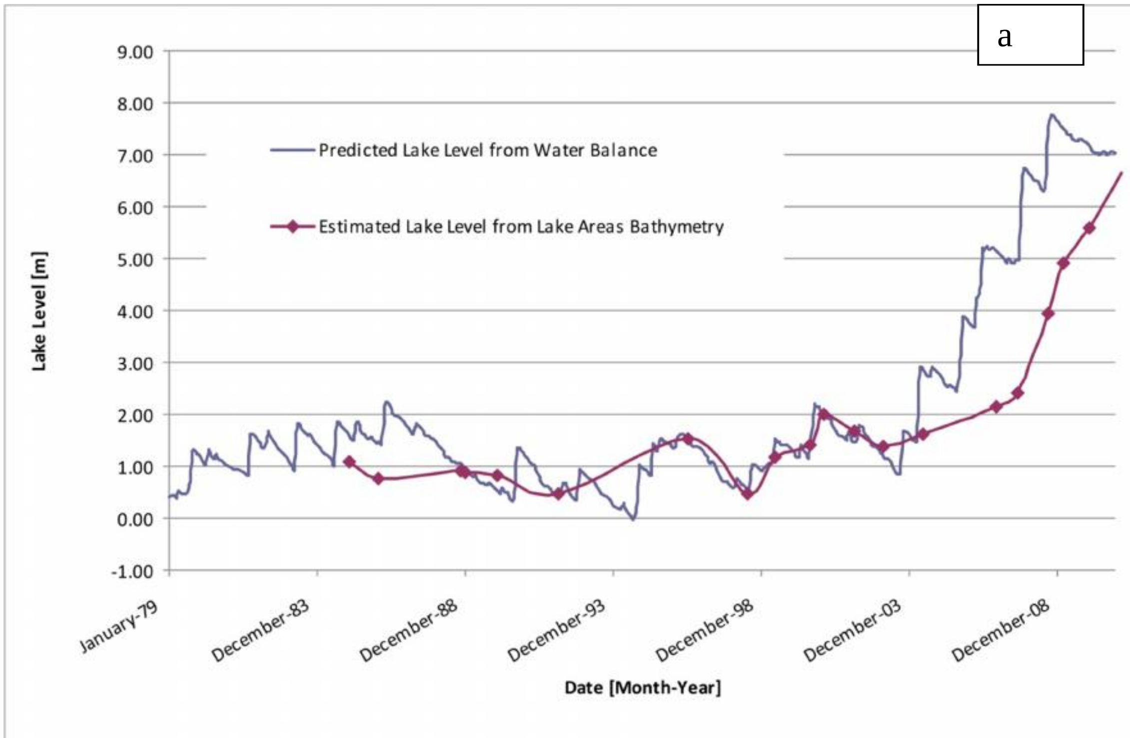


Figure 4: Rainfall-runoff relationship for a cloud forest watershed in the La Tigra National Park, Honduras.


a
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
-1.00
Lake Level [m]
Predicted Lake Level from Water Balance
Estimated Lake Level from Lake Areas Bathymetry
January-79
December-83
December-88
December-93
December-98
December-03
December-08
Date [Month-Year]

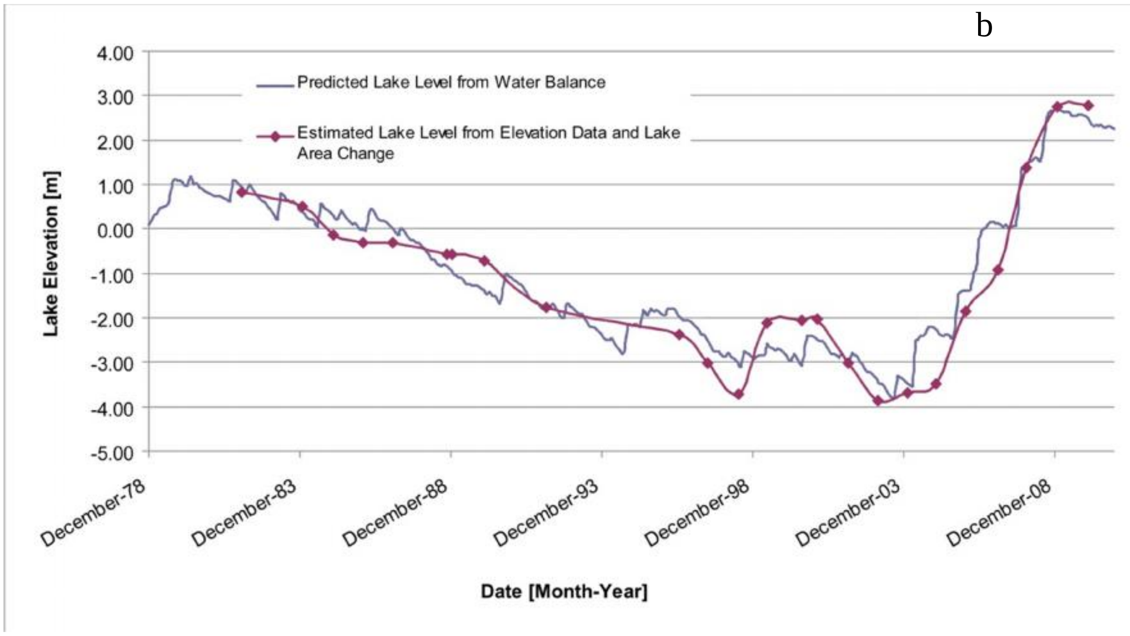


Figure 5: Simulated and measured lake elevation from 1979 to 2010. a) Lake Saumatre , b) Lake Enriquillo

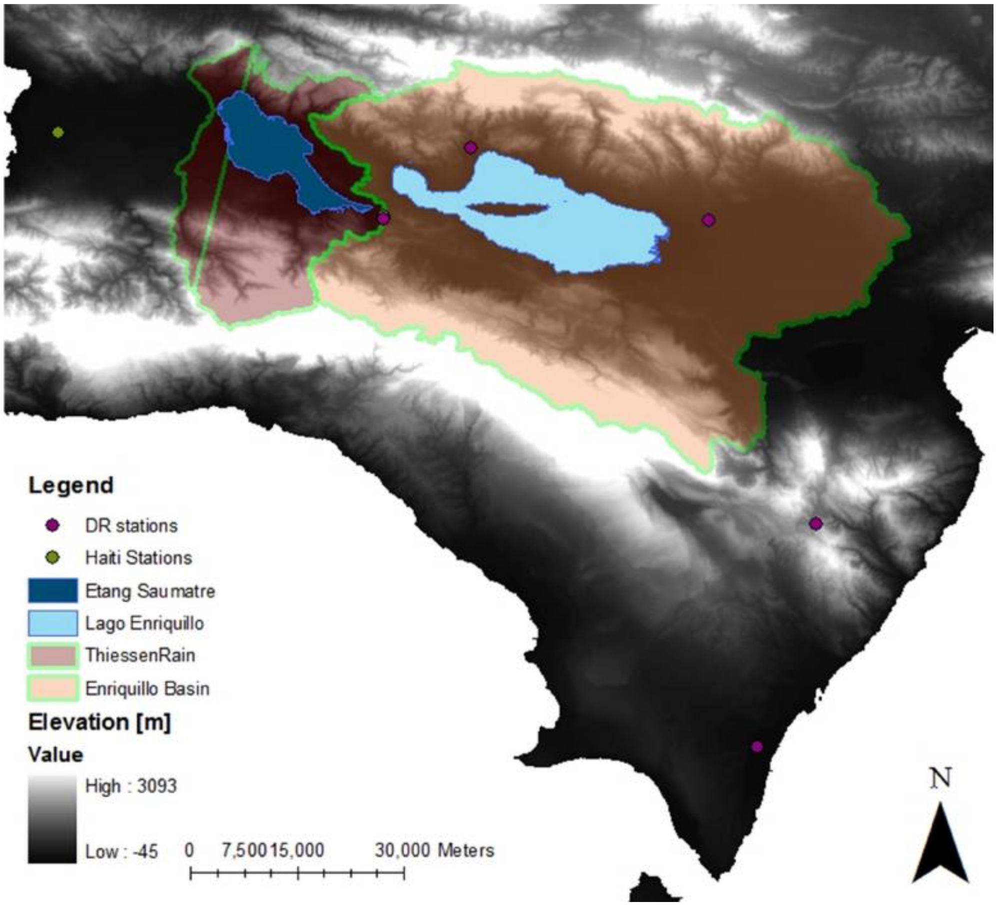


Figure S1a: Surface areas of Lake Saumatre (left) and Lake Enriquillo (right) and their watersheds

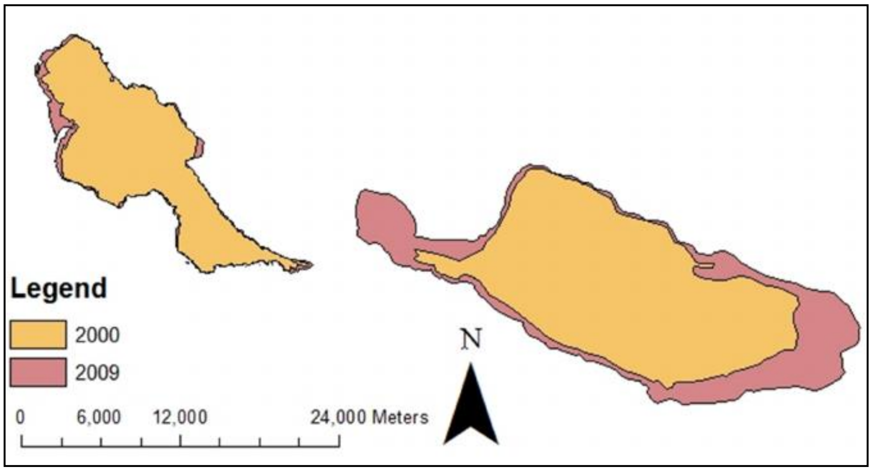
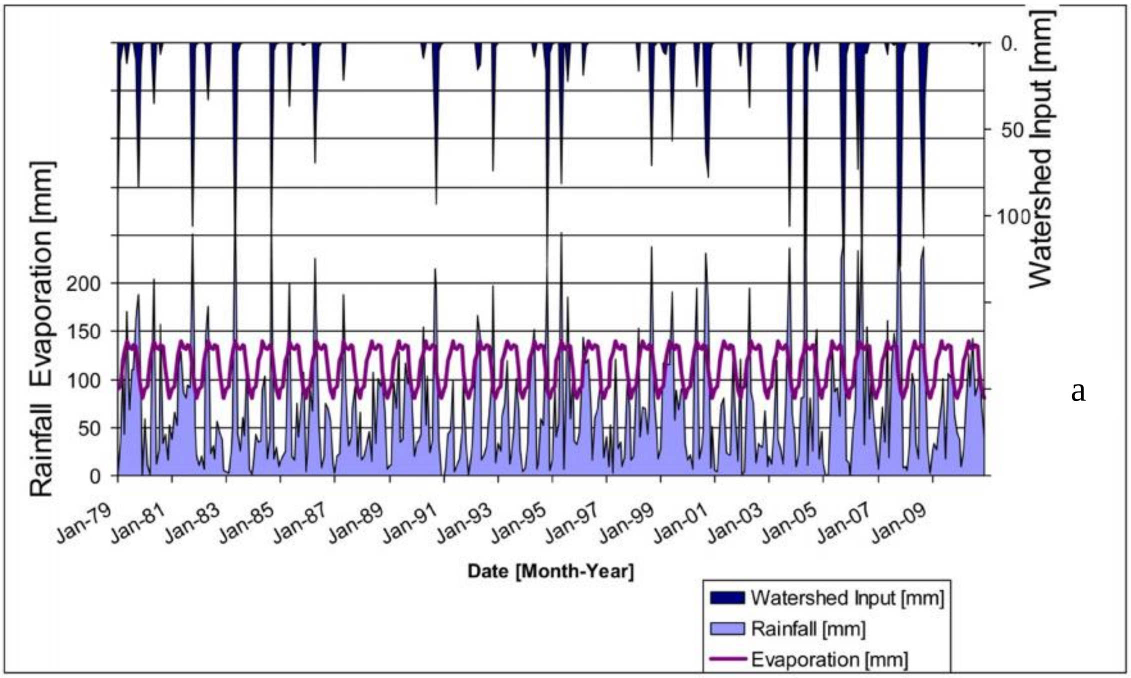


Figure S1b: Surface areas of Lake Saumatre (left) and Lake Enriquillo (right) in 2000 and 2009



Rainfall Evaporation [mm]
Watershed Input [mm]
0
50
100
150
200
0.
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Jan-99
Jan-01
Jan-03
Jan-05
Jan-07
Jan-09
Date [Month-Year]
Watershed Input [mm]
Rainfall [mm]
Evaporation [mm]

a

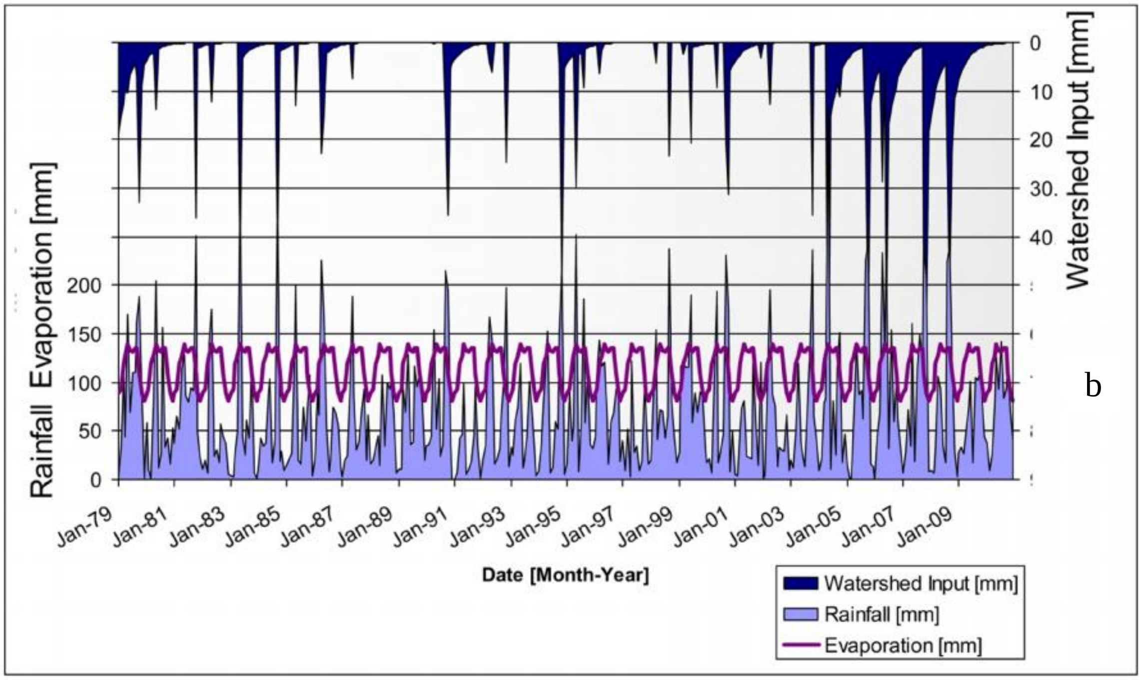


Figure S2: Water balance for the lake, with the amount od water contributed from the watershed, potential evaporation and rainfall. a. Lake Saumatre b. Lake Enriquillo