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# WATER BALANCE AND NUTRIENT EXPORT MODELING USING WEAP: CONSTRAINTS TO MODEL THE EFFECTS OF FOREST RESTORATION AND CLIMATE CHANGE IN THE UPPER GRIJALVA RIVER BASIN

# MODELACIÓN DEL BALANCE HÍDRICO Y EL MOVIMIENTO DE NUTRIENTES UTILIZANDO WEAP: LIMITACIONES PARA MODELAR LOS EFECTOS DE LA RESTAURACIÓN FORESTAL Y EL CAMBIO CLIMÁTICO EN LA CUENCA ALTA DEL RÍO GRIJALVA

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## Abstract

This paper reports projected effects of forest restoration in water balance and nutrient export considering current climate conditions, water demands, population growth and future climate change scenarios in the upper Grijalva river basin using WEAP (Water Evaluation And Planning). We used data obtained from two catchments and four sub-catchments, including climate, population density, municipal water demands, forest, and land use cover, as well as periodic base flow measurements, and nitrogen and phosphorus water concentration from the year 2012. Changes in land use and its effect in keeping water security, considering population growth and climate change were analyzed for a 15 years span (considering 2012 as a base year). Specifically, we modeled substitution of bare ground and open shrublands to pine-oak forests. Our forest restoration scenario consists of increasing pine oak forest cover from 7.4% to 20.9% of area in Xelaju river catchment; and from 9.8% to 18.3 % of area in the Bacanton river catchment and is based in previous work suggesting local willingness to move forward to forest restoration practices. Our results show that restoration activities could prove effective in decreasing nutrient export. In Xelaju and Bacanton river catchments decreases of 8,561 and 1,870 kg were observed in nitrogen generation respectively; and decreases of 2,335 and 551 kg in phosphorus generation, respectively. Projected water balance suggests that in case of a forest restoration, evapotranspiration will reduce and infiltration and surface runoff will increase. Evapotranspiration reduction and increase in surface runoff is not consistent with literature and could reflect the lack of proper data to model for local conditions. On the other hand, infiltration increases showed more consistency with literature. Due to other unexpected results, we recommend further generation of data at a local level to incorporate and enrich the WEAP model in order to reach more reliable results. Finally, we recommend actions taken towards forest restoration in the study area.

**Keywords**: water availability, nitrogen, phosphorous, soil cover, pine-oak forest.

## Resumen

Este estudio proyecta los efectos de la restauración forestal sobre el balance hídrico y el movimiento de nutrientes considerando las condiciones climáticas actuales, la demanda de agua, el crecimiento poblacional y los escenarios futuros de cambio climático en la cuenca alta del río Grijalva mediante el uso del modelo WEAP (Water Evaluation And Planning). Se utilizaron datos obtenidos en dos cuencas y cuatro subcuencas, incluyendo clima, densidad poblacional, consumo de agua, uso de suelo y cobertura de bosques, así como mediciones periódicas de caudales base, y de concentraciones de nitrógeno y fósforo en agua en el año 2012. Los cambios de uso de suelo y su efecto en el mantenimiento de la seguridad hídrica, considerando el crecimiento poblacional y el cambio climático fueron analizados para un periodo de 15 años (partiendo del 2012 como año base). Específicamente, se modeló la sustitución de los suelos en barbecho y la selva baja por bosques de pino-encino. El escenario de restauración forestal proyecta un incremento de área de bosque de pino-encino de 7.4% a 20.9% en la cuenca del río Xelajú; y de 9.8% a 18.3% en la cuenca del río Bacantón y se basa en un trabajo previo que identificó la voluntad local de realizar estas prácticas de restauración forestal. Nuestros resultados mostraron que las actividades de restauración forestal producen un efecto positivo en la disminución de las concentraciones de nutrientes en el agua. En las cuencas de los ríos Xelajú y Bacantón se observó una disminución en la generación de nitrógeno de 8,561 y 1,870 kg, respectivamente; y una disminución en la generación de fósforo de 2,335 y 551 kg, respectivamente. Sin embargo, el balance hídrico proyectado para el futuro sugiere que, en el caso de realizarse la restauración forestal, habrá una reducción en la evapotranspiración y un aumento en la infiltración y en la escorrentía superficial. La reducción de la evapotranspiración y el incremento de la escorrentía superficial no es consistente con la mayoría de los resultados encontrados en la literatura y podría reflejar la falta de datos apropiados para la modelación de las condiciones locales. El incremento de la infiltración si está más acorde con la literatura. Debido a los anteriores resultados inesperados recomendamos mayor generación de datos a nivel local para incorporar y enriquecer el modelo WEAP y obtener resultados más confiables. Finalmente, recomendamos algunas acciones de restauración forestal en el área de estudio.

**Palabras clave:** disponibilidad de agua, nitrógeno, fósforo, cobertura de suelo, bosque de pino-encino.

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## INTRODUCTION

Nearly 80% of the world's population is exposed to high levels of threat to water security (Vorosmarty *et al.*, 2010). Growing problems of water scarcity, environmental degradation, food insecurity and poor livelihood conditions and human health all require urgent policies and management measures, pointing attention to the inclusion of interrelationships between forests and water in land use and planning (De Groot *et al.*, 2010). According to Johnson *et al.* (2001), scientists can help by developing future scenarios and evaluating possible management options. Information on best practices for policy-makers remains scarce and models for predicting responses in individual catchments are at best approximate (Stolton and Dudley, 2007). Forest ecosystem services are receiving increasing attention in the scientific research and policy arena (Kauffer and Medina, 2014; Sharachchandra, 2009). Forested areas provide alternative valuable ecosystem services such as carbon sequestration, water percolation and filtration, soil erosion control and biodiversity (Guevara-Escobar *et al.*, 2007). Forested watersheds with healthy forests, in comparison with other land uses, strongly influence the quantity and quality of water yielded from catchments (Zingari and Achouri, 2007). However, forests can only supply conservation and protective functions if preserved under natural conditions or harvested under a sustainable management (Gottle and Sène, 1997).

Over the last decade, 13 million ha/year of forests have been deforested in the world (Moutinho, 2012). The current scale of deforestation in tropical regions and the large areas of degraded lands underscore the urgent need for interventions to restore biodiversity, ecological functioning, and the supply of goods and ecological services used by communities in the past (Lamb *et al.*, 2005). According to Körner and Ohsawa (2006), twenty percent of the world's human population (1.2 billion inhabitants) live in mountains or at their edges, and half of humankind depend in one way or the other on mountain resources and ecosystems mostly for water provision.

High rates of deforestation and forest fragmentation have also affected extensive areas of the forest of southern Mexico (Cayuela *et al.*, 2006; Ochoa-Gaona and Gonzalez-Espinosa, 2000). The montane forests of southern Mexico and Guatemala are highly diverse formations that include pine-oak forests, deciduous forest, and montane cloud forest, among others (Breedlove, 1981) . In addition to occasional natural perturbations (landslides, windstorms, fire), these forests have been subject for centuries to a wide range of human disturbances derived from slash-and-burn *milpa* agriculture (Gonzalez-Espinosa *et al.*, 2006).

Forest restoration seems not only urgently needed but as a viable option for the recovery of forest services and products as well (Gonzalez-Espinosa *et al.*, 2008). The objective of this research is to project the effects of forest restoration on water resource, specifically water balance and water nutrients export (N and P) using WEAP (Water Evaluation and Planning) software, considering climate change scenarios and focusing in unmet demands and the potential of forest restoration to supply, in further years, the needs of the population.

## METHODOLOGY

### Study Area

Our research was conducted in 116 km$^2$ area delimited by the water-divide of the Xelaju and Bacanton river catchments (catchments 6 and 5, respectively – in Figure 1), located in the transboundary upper Grijalva river basin in the border between Mexico and Guatemala. Xelaju river catchment is located entirely in Mexico; Bacanton river catchment includes Guatemalan territories upstream and Mexican territories downstream (Figure 1). We focused on this area since it was part of the Grijalva River Project carried out by *El Colegio de la Frontera Sur* between 2011 and 2012. Base flows as well as N and P concentration were measured in both rivers gauge points and in four sub-catchments of the Xelaju catchment (Allende catchment 1, Buenos Aires catchment 2, Molino catchment 3, and Carrizal catchment 4).

Located in the highlands of Chiapas, the study area is characterized by steep slopes ranging from *7.14% to 20.74% and with* elevations *between 1,050 and 2,560 meters above sea level (Simulador de Flujos de Agua de Cuencas Hidrográficas (SIATL) of Instituto Nacional de Estadística y Geografía - INEGI, 2013). The area is* dominated by a landscape of peasant farming, remnants of disturbed pine and pine-oak forests, deciduous forests and shrublands. The largest population settlement is the municipality of Motozintla de Mendoza located in the center of Xelaju river catchment (Figure 1), with 23,755 people according to the census data from INEGI (2010). Descriptive information for each catchment in the study area is presented in Table 1, estimated from INEGI 2010 census data and interpretation of SPOT satellite imagery of 2011 according to Laino-Guanes *et al.* (2014).

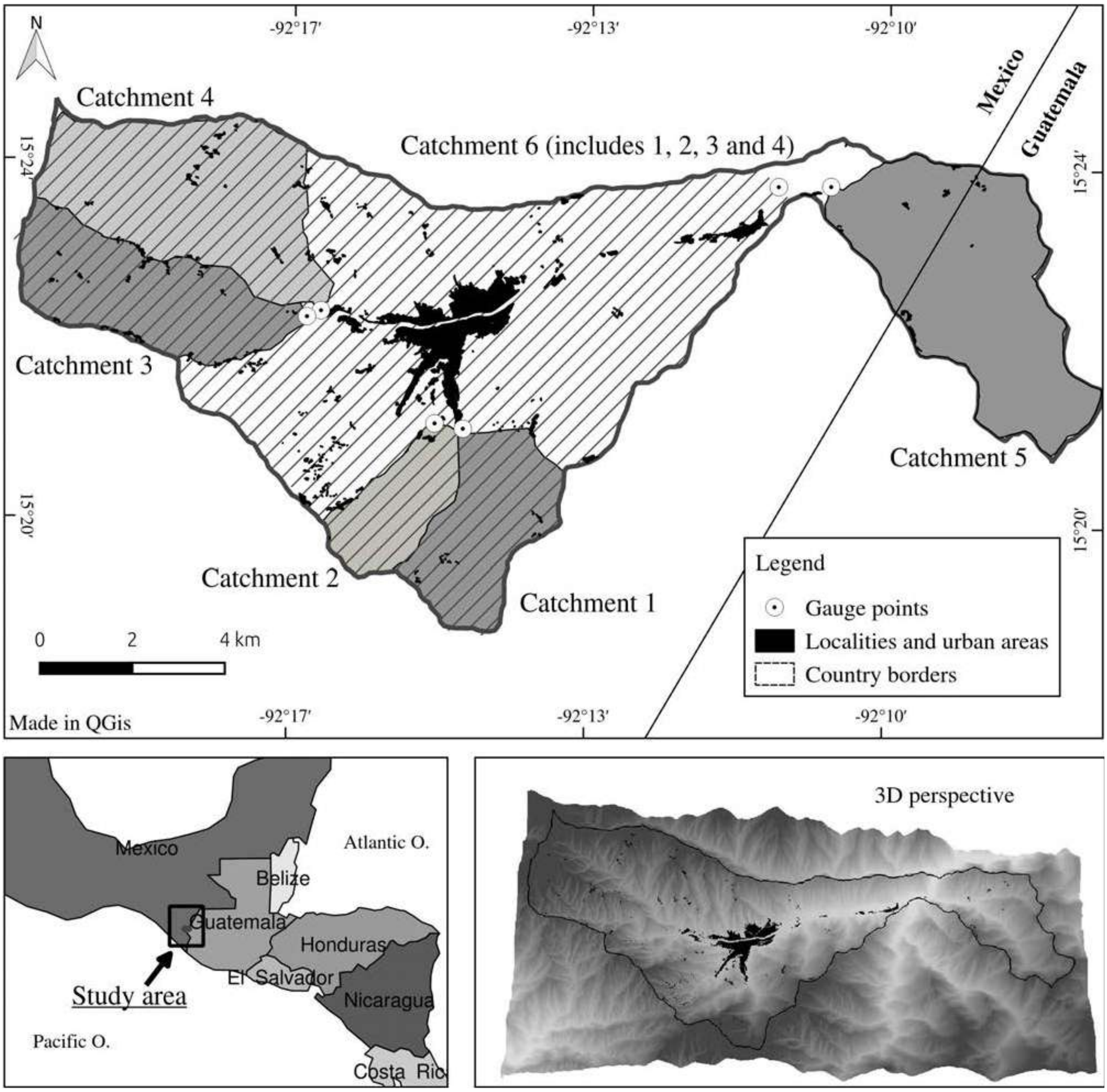

**Figure 1.** Xelaju and Bacanton river catchments in the upper Grijalva river basin (Mexico-Guatemala border). Measurements for water nutrients concentration (N and P) and base flow were sampled in gauge points of the Allende (1), Buenos Aires (2), Molino (3), Carrizal (4), Bacanton (5) and Xelaju (6) catchments

**Table 1.** Land area and population density of studied catchments and sub-catchments in the Mexico-Guatemala border

| **Catchment** | **1** | **2** | **3** | **4** | **5** | **6** |
|---|---|---|---|---|---|---|
| River | Allende | Buenos Aires | Molino | Carrizal | Bacanton | Xelaju |
| Population (total No. people) | 563 | 179 | 1,498 | 1,751 | 2,321 | 33,068 |
| Land area (ha) | 884 | 532 | 1,146 | 1,693 | 1,968 | 9,728 |
| Population density (No. people/ha) | 0.64 | 0.34 | 1.31 | 1.03 | 1.18 | 3.40 |

## Data collection

Six sampling campaigns were conducted during 2012 to determine N and P water concentration and base flows, three of them in the dry season (January, April and December), and three in the rainy season (June, August and October). In each of these campaigns, grab samples were collected from the gauge points of the six catchments under base flow conditions. A total of 36 water samples were collected to test for nitrogen (N) and phosphorus (P) water concentration. N and P were analyzed according to HACH's (2005) persulphate digestion method 10071 and molybdovanadate method 10127, respectively. Base flows in the gauge points were calculated at the time of water sample collection. Flow velocity was measured by means of a flow probe (FP101 Global Flow Probe) following the user's manual recommendations (Global Water, 2004). In cases where rivers were too shallow or with a high content of stones, the float method was applied according to Villon Bejar (2002). Cross sections were drawn and estimated using AutoCAD software to calculate base flows.

Forests within our study area have been heavily affected by natural and anthropogenic disturbances, and transformed to agricultural lands, despite pronounced slopes that represent higher vulnerability to landslides (Gomez-Pineda *et al.*, 2014). Forest remnants are composed mainly by pine trees and *Quercus* and are severely disturbed (Ramirez-Marcial *et al.*, 2014). Deciduous forest and montane cloud forest can also be found in the study area. Vegetation classes from the Grijalva River Project were reclassified after field work (Table II) by Ramirez-Marcial *et al.* (2014) and field observations from the same project carried out in 2011-2012 with the purpose of validating unsupervised vegetation classes using field data. We used QGIS (Quantum GIS) to reclassify in combination with Openlayers plugin visual confirmation. Guatemala vegetation cover was obtained from interpretation of satellite imagery and field trips. Vegetation cover types used for WEAP modeling can be found in Table 2.

**Table 2.** Percent of land cover of study area, estimated from Grijalva River Project vegetation classes map modified by Ramirez-Marcial et al. (2014); Guatemala forest cover estimated from field work observation and satellite imagery (Open Layers Plugin on QGIS)

| Land Cover (%) | Allende | Buenos Aires | Molino | Carrizal | Bacanton | Xelaju |
|---|---|---|---|---|---|---|
| Agricultural land | 31.6 | 6.4 | 43.7 | 41.4 | 45.2 | 39.4 |
| Bare ground | 0.8 | 0.6 | 4.5 | 4.5 | 1.7 | 3.3 |
| Deciduous forest | 1.0 | 0.0 | 8.1 | 1.9 | 20.3 | 11.3 |
| Grassland | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 |
| Hydrophilic vegetation | 0.6 | 0.4 | 0.1 | 0.1 | 0.2 | 0.9 |
| Montane cloud forest | 0.0 | 0.0 | 18.2 | 0.0 | 0.0 | 2.2 |
| Open shrubland | 5.0 | 6.4 | 10.4 | 7.8 | 6.8 | 10.2 |
| Pine forest | 60.4 | 85.2 | 0.0 | 10.5 | 13.3 | 18.3 |
| Pine-oak forest | 0.0 | 0.0 | 11.8 | 30.3 | 9.8 | 7.4 |
| Riparian forest | 0.0 | 0.0 | 0.0 | 0.0 | 0.7 | 0.5 |
| River bed | 0.1 | 0.2 | 2.5 | 2.9 | 1.6 | 2.6 |
| Settlement | 0.3 | 0.6 | 0.8 | 0.6 | 0.3 | 3.8 |

Nitrogen (N) and phosphorus (P) export values for each kind of soil cover considered in WEAP modeling are presented in Table 3. There are few studies about nutrient export in Mexico (such as Izurieta *et al.*, 2001), for this reason references to USA and Australian data were used in this research. Crop coefficient (Kc) values for each kind of land cover were obtained based on Amador-Garcia *et al.* (2011) and Allen *et al.* (1998). Annual water consumption per person in Mexico used for WEAP modeling was of 130 m$^3$ according to *Centro Virtual de Información del Agua* (2014). Precipitation data was obtained from *Buenos Aires weather station, administered by the Comisión Nacional del Agua (CONAGUA), and located at 1,720 meters above sea level, 15º19`57`` North and 92º16`03`` West.* Annual precipitation since 1982 is shown in Figure 2. Precipitation patterns present much variability, ranging from less than 500 mm (in 1996) to almost 2,500 mm (in 2010) of annual precipitation. In addition, data for several years is missing (35% of total data). Based on this high variability and information gap, we classified the years according to the annual precipitation: very dry (less than 618 mm), dry (618 - 1,047 mm), normal (1,047 – 1,377 mm), wet (1,377 – 1,877 mm) and very wet (more than 1,877 mm) years.

**Table 3.** Nitrogen (N) and phosphorus (P) export values for each kind of soil cover

| Soil Cover | N (kg/ha/yr) | P (kg/ha/yr) | Source of N and P export values |
|---|---|---|---|
| Agricultural land | 9 | 3 | Between ranges proposed by Browne and Grizzard (1979), Beaulac and Reckhow (1982), Frink (1991), Sonzogni **et al.** (1980) |
| Bare ground | 3 | 0.67 | Between ranges proposed by Browne and Grizzard (1979), Sonzogni **et al.** (1980) |
| Grassland | 2 | 0.2 | Between ranges proposed by Cullen (1991), Beaulac and Reckhow (1982) |
| Hydrophilic vegetation | 6 | 0.2 | Glandon **et al.** (1981) |
| Forest | 1 | 0.07 | Between ranges proposed by Browne and Grizzard (1979), Cullen **et al.** (1988), Sonzogni **et al.** (1980), Rosich and Cullen (1982) |
| Open shrubland | 0.9 | 0.03 | Chittleborough (1983) |
| Riparian forest | 1 | 0.07 | Between ranges proposed by Browne and Grizzard (1979), Cullen **et al.** (1988), Sonzogni **et al.** (1980), Rosich and Cullen (1982) |
| Settlement | 8 | 1.2 | Between ranges proposed by Sonzogni **et al.** (1980), Frink (1991), Loehr (1974), Beaulac and Reckhow (1982), Graham (1989), Young **et al.** (1996) |

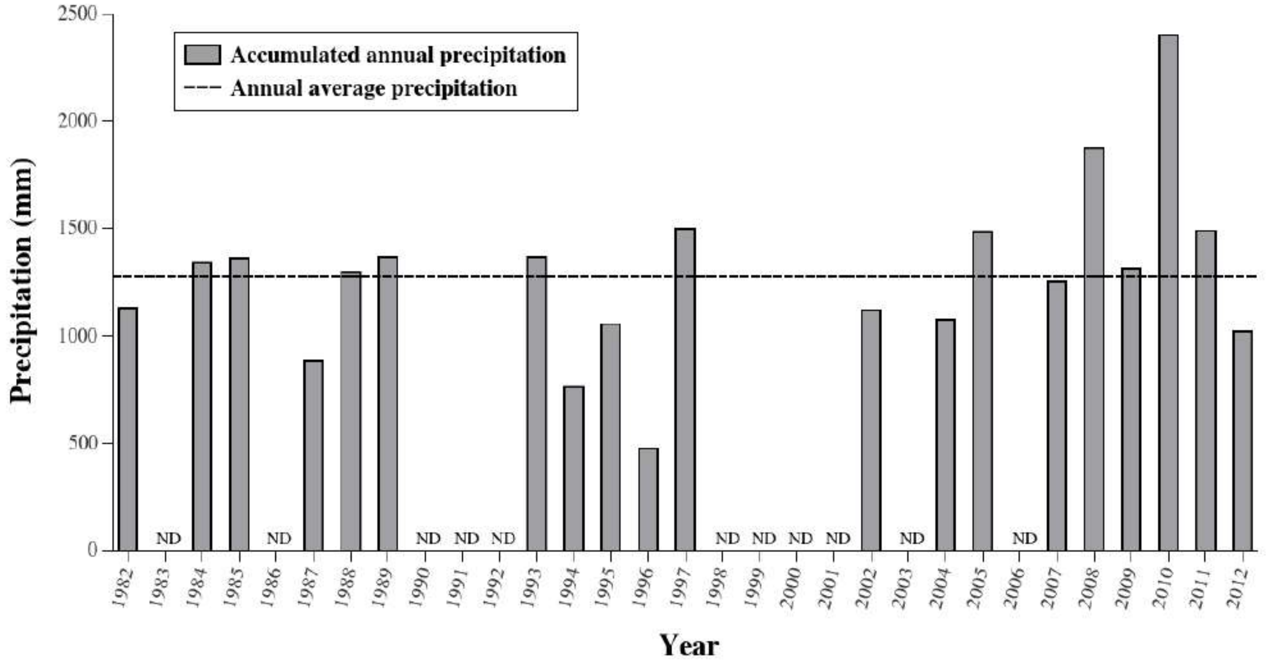

**Figure 2.** Annual precipitation according to data obtained from Buenos Aires meteorological station for 1982-2012 period. Data of the years 1983, 1986, 1990, 1991, 1992, 1998, 1999, 2000, 2001, 2003 and 2006 were omitted due to incomplete records (ND = no data). Source: CONAGUA, 2013

*Annual average precipitation is 1,278 mm according to historical data (since 1982). Annual precipitation recorded for base year (2012) of this study was 1,020 mm (less than the historical average), falling in the dry year category. T*he study area has two well marked seasons: rainy season from May to October, and dry season from November to April, with an intraestival drought period observed between July and August. This period was also clearly observed in July for the base year (Figure 3). Monthly average temperature data was obtained from *Buenos Aires weather station (CONAGUA, 2013).* Monthly reference evapotranspiration for base year 2012 in the study area is presented in Table 4, calculated from average temperature through Thornthwaite method as described by Villon Bejar (2001). According to this method, potential annual evapotranspiration on 2012 was 791 mm, equivalent to a 77.6% of the historical annual precipitation. Rainfall runoff method (simplified coefficient method) was selected to simulate runoff and infiltration catchment processes. This method determines evapotranspiration for irrigated and rainfed crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration becomes surface runoff, or can be proportionally split as surface runoff and flow to groundwater. Infiltration data used for the model was taken from a work carried out in Honduras by Sosa *et al.* (2001).

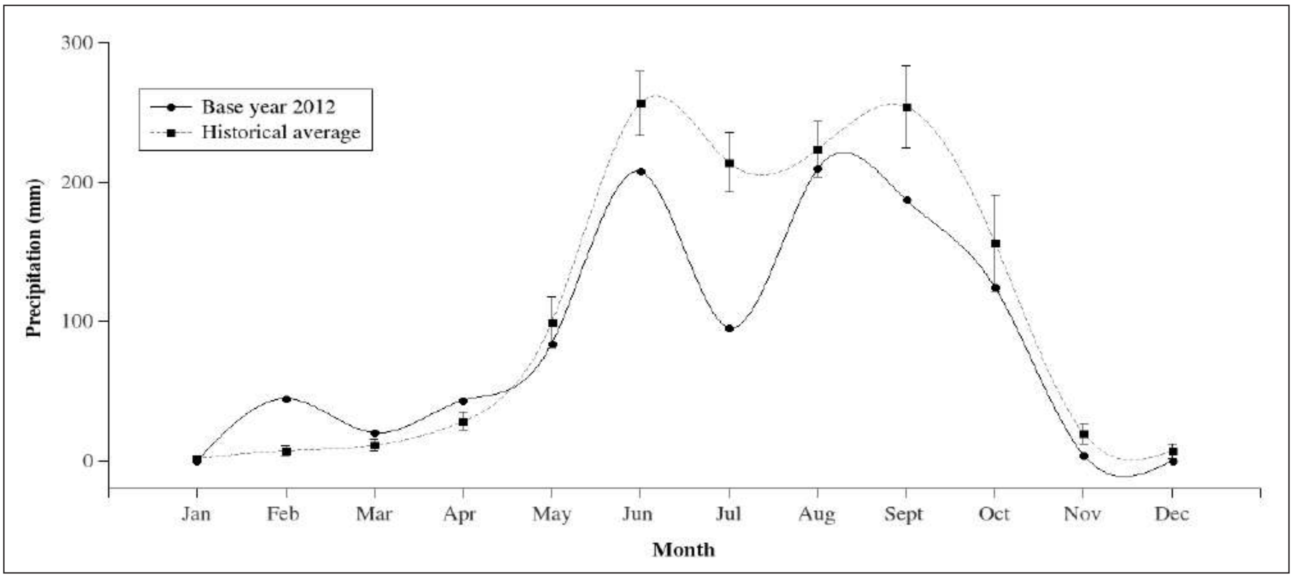

**Figure 3.** Historical monthly average precipitation (S.E.) and monthly precipitation registered on 2012. Source: CONAGUA, 2013

**Table 4.** Monthly reference evapotranspiration calculated through Thornthwaite method for study area

| Month | T media | iIndex | E (MM) | f factor | ec (mm) |
|---|---|---|---|---|---|
| **Jan** | 16.1 | 5.890 | 56.0 | 0.970 | 54 |
| **Feb** | 16.7 | 6.202 | 59.5 | 0.910 | 54 |
| **Mar** | 17.2 | 6.509 | 62.9 | 1.030 | 65 |
| **Apr** | 17.9 | 6.884 | 67.2 | 1.040 | 70 |
| **MAY** | 18.6 | 7.296 | 71.9 | 1.110 | 80 |
| **Jun** | 18.0 | 6.937 | 67.8 | 1.080 | 73 |
| **Jul** | 18.0 | 6.966 | 68.1 | 1.120 | 76 |
| **Aug** | 18.1 | 7.019 | 68.7 | 1.080 | 74 |
| **Sept** | 18.0 | 6.978 | 68.3 | 1.020 | 70 |
| **Oct** | 17.3 | 6.560 | 63.5 | 1.010 | 64 |
| **Nov** | 15.9 | 5.741 | 54.4 | 0.950 | 52 |
| **Dec** | 16.9 | 6.338 | 61.0 | 0.970 | 59 |

T media: monthly average temperature (°C). Source: *CONAGUA (2013).*
i Index: monthly thermal index, besides I= sum of i= 79,319.
e: uncorrected monthly evapotranspiration (mm), where a= 1,765.
f factor: correction factor for latitude of 15° North.
ec: corrected monthly evapotranspiration (mm).

## WEAP software tool

WEAP (Water Evaluation And Planning) is a software tool for integrated water resources planning that attempts to assist rather than substitute for the skilled planner. The Stockholm Environment Institute provided primary support for its development. WEAP operates on the basic principle of a water balance and can be applied to municipal and agricultural systems, a single watershed or complex transboundary river basin systems. Moreover, WEAP can simulate a broad range of natural and engineered components of these systems, including rainfall runoff, baseflow, and groundwater recharge from precipitation. The data structure and level of detail can be easily customized to meet the requirements and data availability for a system and analysis (http://www.weap21.org). Figure 4 shows schematic representation of the WEAP model.

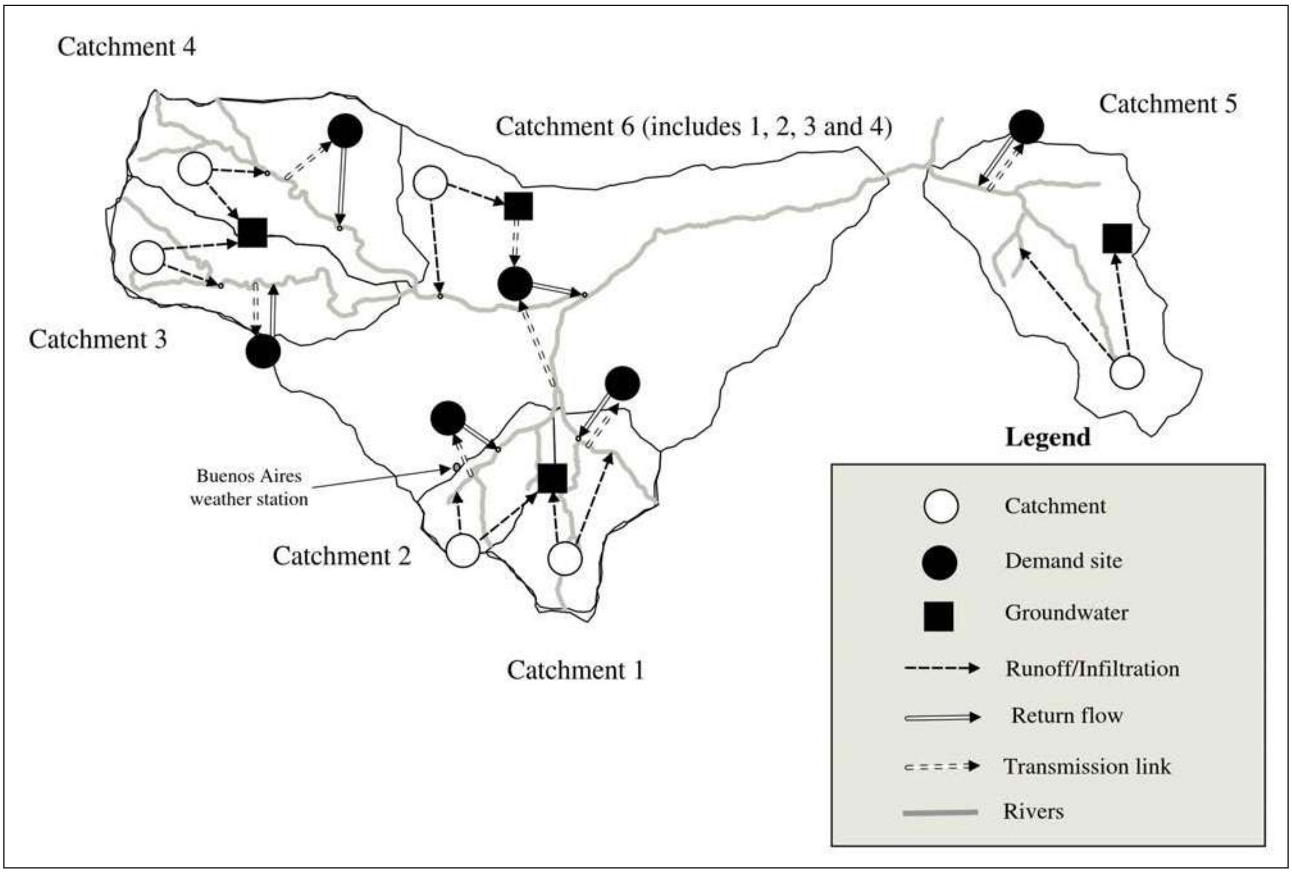

**Figure 4.** Schematic representation of WEAP model used to estimate water balance and impacts of future restoration scenarios. Features of the model for each catchment include: 'Rivers' (gray sinuous line), 'Catchment' area (white circle),water 'Demand site' (black circle), 'Transmission link' from the source (surface and/or groundwater) to the demand site (segmented double lines arrow), 'Return flow' (double solid lines arrow) or population water discharge, 'Runoff/Infiltration' sections (segmented line arrow), and 'Groundwater' (black square). Sub-catchment and river sections have been linked to obtain a complete model of the study area

## Future projections

Previous studies in this area (Laino-Guanes et al., 2014) have shown a dependency on superficial rivers for water supply for the city of Motozintla and neighboring localities, specifically from rivers Allende, Buenos Aires and Carrizal (catchments 1, 2 and 4 respectively – Figure 1). This dependence on stream flows becomes critical during the dry season, which can last up to six months (Figure 3). The situation might become even more problematic considering population growth, climate change and the reduction of forest cover in small catchments. From the livelihood perspective, even though local actors show 'willingness' to move towards forest restoration strategies, concrete activities have not taken place (Gomez-Pineda et al., 2014).

We projected the effects of the active forest restoration in water balance and nutrient (N and P) exports. Changes were projected for a fifteen year span, starting in 2012 as a base year. Population growth and climate change were also included in forest restoration projections. Population growth rate was obtained from *Consejo Nacional de Población* (CONAPO, 2012), available estimations show a decrease in population growth from 1.92% in 2012 to 1.03% in 2027 for Motozintla de Mendoza.

We projected a future scenario based on climate change according to REDDEAM (2013). The trend in precipitation is a change of -37.9 mm per decade. The p-value under a linear model is 0.002 (statistically significant). According to this trend, in 15 years a decrease of -56.8 mm of annual precipitation is expected and 2027 will be a normal year with 1,221 mm of annual precipitation. This value was modified proportionally for each month based on the historical data from CONAGUA (2013). Historical monthly mean precipitation, monthly precipitation registered on 2012 and monthly precipitation projected for 2027 are shown in Table 5. For active forest restoration, we projected future change of soil uses, considering if current areas 'bare ground' and 'open shrubland' were transformed into 'pine-oak forest'. Table 6 shows current and future forest soil cover in each catchment.

**Table 5.** Historical monthly mean precipitation and S.E., monthly precipitation registered on base year (2012) and monthly precipitation projected for year 2027. Precipitation data is reported in mm

| Month | *Jan* | *Feb* | *Mar* | *Apr* | *May* | *Jun* | *Jul* | *Aug* | *Sept* | *Oct* | *Nov* | *Dec* | *Total* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Historical mean precipitation | 1.6 ±0.9 | 7.1 ±3.3 | 10.9 ±4.1 | 28.2 ±6.4 | 99.3 ±18.5 | 256.6 ±22.8 | 214.2 ±21.5 | 223.5 ±19.9 | 254.1 ±29.3 | 156.4 ±34.5 | 19.5 ±7.6 | 7 ±5 | 1,278 ±90 |
| Base year (2012) | *0* | *44.5* | *20* | *43.2* | *83.9* | *207.5* | *95.5* | *209.6* | *187.2* | *124.3* | *4* | *0* | *1,019.7* |
| Projections (2027) | 1.5 | 6.8 | 10.5 | 27.0 | 94.9 | 245.2 | 204.6 | 213.5 | 242.8 | 149.4 | 18.7 | 6.7 | 1,221.2 |

**Table 6.** Current (year 2012) and future (year 2027) pine-oak forest area (% cover) in each catchment

| **Current soil cover (2012)** | **Allende** | **Buenos Aires** | **Molino** | **Carrizal** | **Bacanton** | **Xelaju** |
|---|---|---|---|---|---|---|
| | **Percent of area (%)** | | | | | |
| **Pine-oak forest** | 0 | 0 | 11.8 | 30.3 | 9.8 | **7.4** |
| **Bare ground** | 0.8 | 0.6 | 4.5 | 4.5 | 1.7 | **3.3** |
| **Open shrubland** | 5 | 6.4 | 10.4 | 7.8 | 6.8 | **10.2** |
| **Active forest restoration scenario (2027)** | | | | | | |
| Pine-oak forest | 5.8 | 7 | 26.7 | 42.6 | 18.3 | 20.9 |
| Bare ground | 0 | 0 | 0 | 0 | 0 | 0 |
| Open shrubland | 0 | 0 | 0 | 0 | 0 | 0 |

Our active forest restoration scenario consists of increasing pine-oak forest cover from 7.4% to 20.9% in Xelaju river watershed; and from 9.8% to 18.3 % in Bacanton river watershed. Our scenarios, are originated from previous studies showing which areas would be locally 'acceptable' by local actors to be considered for forest restoration (Gomez-Pineda et. al., 2014), assuming all communities in the study area would be willing to do so.

## RESULTS AND DISCUSSION

Data of base flow, N and P concentrations recorded in gauge points of six catchments in base year (2012) are presented in Table 7.

**Table 7.** Mean (±S.E.) of base flow (l/min) and nitrogen and phosphorus water concentrations (mg/l) recorded in six catchments of the study area in base year 2012

| Catchment | Base flow (l/min) | N (mg/l) | P (mg/l) |
|---|---|---|---|
| Allende | 4,663±1,557 | 0.61±0.23 | 0.69±0.09 |
| Buenos Aires | 2,188±881 | 0.47±0.14 | 0.77±0.10 |
| Molino | 859±439 | 0.60±0.21 | 0.63±0.03 |
| Carrizal | 2,434±1,675 | 0.73±0.48 | 0.60±0.04 |
| Bacanton | 2,501±791 | 0.40±0.14 | 0.81±0.13 |
| Xelaju | 34,783±3,994 | 2.73±0.69 | 1.41±0.20 |

### Effects of active forest restoration in water balance

According to observed precipitation in 2012, base year was classified as a dry year (Figure 2 and Table 5). Precipitation projected for 2027 shows that it will be a normal year. Water balance projected for 2027 obtained from WEAP model is presented in Table 8, considering two scenarios: with and without active forest restoration. Water balance projected for year 2027 shows: (1) in both scenarios, with and without active forest restoration, Allende and Buenos Aires river catchments (more forested catchments – see Table 2) showed higher surface runoff and lower water infiltration (flow to groundwater) than other catchments; evapotranspiration was similar for all catchments. (2) when comparing the two scenarios, results suggest that in case of forest restoration, increasing forest areas, evapotranspiration will reduce in all catchments, and infiltration and surface runoff will increase.

**Table 8.** Water balance projected for 2027 considering two scenarios: with and without active forest restoration. Values are reported in percentage of precipitation. 'Precip.' = Precipitation, 'Evap.' = Evapotranspiration, 'Flow' = Flow to groundwater, and 'Runoff' = Surface runoff

| Catchment | ***2027 projections (% of precipitation)*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Without forest restoration** | | | | **Active forest restoration** | | | |
| | **Precip.** | **Evap.** | **Flow** | **Runoff** | **Precip.** | **Evap.** | **Flow** | **Runoff** |
| Allende | 100 | -48 | -32 | -20 | 100 | -43 | -35 | -22 |
| Buenos Aires | 100 | -46 | -28 | -26 | 100 | -42 | -31 | -27 |
| Molino | 100 | -48 | -42 | -10 | 100 | -44 | -45 | -11 |
| Carrizal | 100 | -48 | -36 | -16 | 100 | -44 | -39 | -17 |
| Bacanton | 100 | -48 | -39 | -13 | 100 | -44 | -42 | -14 |
| Xelaju | 100 | -48 | -37 | -15 | 100 | -44 | -40 | -16 |

These two results (1 and 2) are unexpected and do not seem congruent with literature because: (1) The first result contradicts several studies (Bruijnzeel, 2004; Gottle and Sène, 1997; Guevara-Escobar *et al.*, 2007; Watkins and Imbumi, 2007) reporting that forested catchments, in comparison with other land uses (like bare ground and open shrublands), reduces the runoff and increases water infiltration due to the presence of forest litter and tree roots. (2) In contrast to the second result, the increase of forested areas, especially in the tropics, leads to higher evapotranspiration (Kiersch, 2000), also a reduction in surface runoff is expected (Mungai, 2004; Schoonover *et al.*, 2006). From our projections, increase in infiltration following an increment of forested areas is congruent with most of reviewed hydrological studies (Gottle and Sène, 1997; Guevara-Escobar *et al.*, 2007; Kiersch, 2000).

Some possible explanations of unexpected results are: (1) Due to the lack of local data, WEAP model was run using hydrological data from Honduras, USA and Australia. Hence, the assumption of external data, not generated locally, could cause the erroneous (not congruent with literature) outcomes. This fact highlights the need of more hydrological studies on behavior and development of pine and oak species and the other land-uses and vegetation types of the study area, and the relationship of these species with hydrological parameters. In addition, more studies about nutrient (N and P) export for each land-use and vegetation type of the study area are needed. (2) Another reason that could explain the unexpected results was the use of data of only one weather station with data from only 20 years; also, potential evapotranspiration for this study was based on Thornthwaite method, however, other estimations based on complementary biophysical variables such as vegetation cover, temperature, radiation, wind, air saturation deficit, could be of use for a better approximation to this parameter.

### Effects of active forest restoration in nutrient export

Nitrogen and phosphorus dynamics were obtained through the Intensity method in WEAP. Nitrogen and Phosphorus generation (kg/ha) calculated for each catchment projected for 2027 are presented in Table 9. Under the assumption of substituting areas of 'bare ground' and 'open shrubland' with 'pine-oak forest,' nutrient (N and P) concentrations will reduce for all catchments. These results are congruent with several studies suggesting that catchments with larger forested areas generally produce water with lower nutrient concentrations (Miller *et al.* 2011, Stadtmüller 1994, Stolton and Dudley 2007, Valiela and Bowen 2002). Xelaju and Bacanton river catchments showed decreases of 0.88 and 0.95 kg/ha of nitrogen generation, respectively; and decreases of 0.24 and 0.28 kg/ha of phosphorus generation, respectively; in our projected 15 years scenario.

**Table 9.** Nitrogen (N) and phosphorus (P) generation (kg/ha) for each catchment projected for 2027 calculated using WEAP, considering two scenarios: with and without active forest restoration

| **2027 projections** | **Allende** | **Buenos Aires** | **Molino** | **Carrizal** | **Bacanton** | **Xelaju** |
|---|---|---|---|---|---|---|
| | **N generation (kg/ha)** | | | | | |
| Without forest restoration | 4.23 | 1.87 | 5.60 | 5.40 | 5.66 | 5.46 |
| Active forest restoration | 3.52 | 1.57 | 4.70 | 4.51 | 4.71 | 4.58 |
| | **P generation (kg/ha)** | | | | | |
| Without forest restoration | 1.18 | 0.31 | 1.63 | 1.55 | 1.68 | 1.51 |
| Active forest restoration | 0.98 | 0.26 | 1.37 | 1.30 | 1.40 | 1.27 |

### Need for future studies and generation of data at a local level

Future projections modeled in this research implied changes on soil cover, considering only type of soil cover, however, it is clearly not enough to support the analysis and modeling of watershed-scale studies only on changes in percentage of forest cover, further studies should also include forest descriptors (Andréassian, 2004).

The role of trees in water balance involves other factors such as canopy structure (Hormann *et al.*, 1996) and the age of trees (Iida *et al.*, 2005). According to Pypker *et al.* (2005) old forests intercept larger amounts of water than younger forests. This larger capacity of mature forests is linked to a higher canopy storage capacity, related in turn to a higher Leaf Area Index and larger epiphyte biomass (Holwerda *et al.*, 2010). Epiphytes, especially mosses and ferns growing on stems retain significant amounts of water (Grimm and Fassbender, 1981).

Forests undoubtedly have an impact on water balance at the basin scale, with studies of deforestation or reforestation not usually contemplating consequences of the aging of forest stands, or of the densification of forest cover at the watershed-scale (Andréassian, 2004). Such factors, specifically forest age and thinning should be incorporated into models used in water resources planning to more accurately predict the hydrological effects of afforestation (Webb and Kathuria, 2012). According to Vallejos-Barra *et al.* (2010) interception depends more heavily on canopy architecture, spatial distribution of trees and type of leaves than on the number of trees per plot. Hence, in addition to the need of more hydrological studies on behavior and development of pine and oak species, we recommend more studies on age, canopy structure and spatial distribution of these species and the relationship of these variables to hydrological parameters. Moreover, seasonal variations are fundamental in analyzing hydrological parameters in a catchment.

## CONCLUSIONS

Our results show that restoration activities of bare ground and open shrublands could prove effective in decreasing nutrient export in the future. In Xelaju and Bacanton river catchments, decreases of 8,561 and 1,870 kg in nitrogen generation (respectively) and decreases of 2,335 and 551 kg in phosphorus generation (respectively) were estimated with our model. However, the projected water balance suggests that in case of an idealistic forest restoration scenario, evapotranspiration will reduce and infiltration and surface runoff will increase. Reduction in evapotranspiration and increase in surface runoff is not consistent with literature and could reflect the lack of proper data to model for local conditions. Increases in infiltration showed more consistency with literature. Due to other unexpected results, we recommended the further generation of data at a local level to incorporate and enrich the WEAP model, and reach more reliable results.

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