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Original Research Article

Human pressure on water quality and water yield in the upper Grijalva river basin in the Mexico-Guatemala border

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ABSTRACT

Forest ecosystems are major providers of high quality water and contribute to maintain a better distribution of base flows during the year. However, these environmental services have been adversely affected by human pressure due to the decline and deterioration of forested areas and the inadequate management of water resources. To better understand the relations between human population, forest area and water quality and yield, at a regional level, we studied six catchments located in the upper Grijalva river basin in the border between Guatemala and Mexico. Measurements of twelve water quality parameters and water yield from nine sampling periods during 2011–2013 were analyzed through PLS (partial least squares) regression, ANOVA and linear mixed models to assess the season effect on water quality and the forest cover effect on water yield. An ordination by PCA (principal components analysis) and Pearson's pair-wise correlations were used to identify association between hydrological and social catchment features (forest cover, protection of riparian buffer strips, population density and urban areas). Our results suggest that overall water quality is higher during the dry season (higher values of dissolved oxygen and lower levels of total dissolved solids, total suspended solids, total phosphorus, chemical oxygen demand and temperature were observed). Water yield is positively related to forest cover and riparian buffer strips, becoming essential in maintaining water security for local populations. Major threats to water flux and their quality are related to human pressures and untreated wastewater discharges, which reduce water quality of the receiving rivers.

1. Introduction

Mountain forest ecosystems are major sources of fresh and clean water, highlighting the importance of their conservation and restoration to enable them to maintain a

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provision of water of high quality and quantity (Ponette-González et al., 2009). According to Körner and Ohsawa (2006), twenty percent (1.2 billion) of the world's human population lives in mountains or surroundings, and half of humankind depends closely on mountain ecosystems mostly for water provision. High rates of deforestation and forest fragmentation have affected extensive areas of the forest of Chiapas (Cayuela et al., 2006; Ochoa-Gaona and Gonzalez-Espinosa, 2000). The montane forests of southern Mexico and Guatemala are highly diverse formations (Breedlove, 1981) that include pine-oak forests, deciduous forest, montane cloud forest, among others. 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 (González-Espinosa et al., 2006). Frequent anthropogenic disturbance, increases the dominance of pine and drastically decreases floristic richness, mostly understory trees (Ramírez-Marcial et al., 2001). Changes in vegetation structure and species composition of the pine-oak forest toward a canopy dominated by pines alter microclimatic conditions inside the forest and are associated with impoverishment and soil compaction (Romero-Nájera, 2000).

Growing problems of water scarcity, environmental degradation, food insecurity and poor livelihood conditions and human health all require urgent policy and management measures, pointing attention to interrelationships between forests and water (Zingari and Achouri, 2007).

This relationship between forests and water has been studied since long time ago (Bosch and Hewlett, 1982; Hibbert, 1967; Van Lill et al., 1980). In the late 60s Hibbert (1967) reported results of thirty-nine studies on the effect of altering forest cover on water yield; taken collectively, these studies revealed that forest reduction increases water yield, and that reforestation decreases water yield. Later, in the same way, several authors argued that forests are major water users in the catchment, and that removing forest biomass increases the amount of water available in the lower areas of the catchment (Bruijnzeel, 2004; Calder et al., 2007; Dung et al., 2012; Nelson and Chomitz, 2006; Ponette-González et al., 2009; Stadtmüller, 1994; Stolton and Dudley, 2007). However, other authors claim that the presence of forests ensures rainfall in the region due to water evapotranspirated by forests, typically returned to the atmosphere with interest; thus, if forests are depleted, a decline in rainfall could be expected, leading to lower runoff over a wider region (Ellison et al., 2012; Salati et al., 1979; Sheil, 2014).

As analyzed in the above mentioned studies, continuous water flow is as relevant as total quantity, in terms of both maintenance of dry-season flow and absence of flooding during periods of heavy rain, in particular under extreme hydrometeorological events (Stolton and Dudley, 2007). Regarding the effects of forest conversion on water flow, "total water production" (total annual flow) must be clearly distinguished from "seasonal distribution of flow" (Bruijnzeel et al., 2011). According to Zingari and Achouri (2007), forested catchments (healthy forests) moderate variations of flow throughout the year, as compared to other land uses. Although natural forests and crops have different effects on flow, they do not show a consistent pattern, where location and types of dominant species in the forest become relevant (Stolton and Dudley, 2007).

In some cases, base flow in the dry season is diminished by the presence of trees because of increased evapotranspiration of the forest in the tropics (Kiersch, 2000). In other cases, forest clearance in semi-arid basins, caused strong decreases in flow in dry seasons due to the reduction of water infiltration and hence groundwater recharge (Mungai et al., 2004; Watkins and Imbumi, 2007). Differently, removing demanding water forest cover to prevent or mitigate droughts is highly recommended in some semi-arid areas (Calder et al., 2007). These examples highlight dissimilar outcomes, which might seem contradictory, but are only a response to local particularities. Expert opinions on forest-water yield remain heterogeneous and examples of diverse responses can be found (Stolton and Dudley, 2007). Despite variations found in certain contexts, literature shows that the presence of forests has in general a positive effect on the water cycle, not only in flow regulation but also improving the quality of water generated in the basin.

Regarding water quality, literature seems more unanimous. Several studies (Miller et al., 2011; Stadtmüller, 1994; Stolton and Dudley, 2007; Zingari and Achouri, 2007) suggest that forested basins generally produce water with lower concentrations of nutrients and sediments. Forested basins provide higher water quality than basins under other land uses, usually because the alternatives (agriculture, grassland, industry or settlements) generate greater amounts of pollutants (Stadtmüller, 1994; Stolton and Dudley, 2007) and (or) tend to destroy soil structure and facilitate erosion and sediment load in water (Schoonover et al., 2006; Zingari and Achouri, 2007). In recent years, the expansion of agriculture toward adjacent forested areas, promoting environmental land use conflicts, was seen as prime cause of enhanced soil erosion (Pacheco et al., 2014; Valle Junior et al., 2014a) with negative consequences on groundwater quality (Valle Junior et al., 2014b) and ecological status of riverine ecosystems (Valle Junior et al., 2015).

Nonetheless, when reviewing dry season *vs* wet season data, we found studies that report contrasting results (Alcocer et al., 1998; Santos et al., 2015a; Somura et al., 2012; Wong and Barrera, 2005); some studies report better water quality during the rainy season and others found the opposite.

Riparian ecosystems link water flux with their terrestrial catchment. Because of this physical proximity, they influence the structure of both aquatic and terrestrial communities and reduce sediment inputs, provide important sources of organic matter, and stabilize stream banks. In addition, riparian buffer strips can reduce inputs of solar radiation, hence the removal of riparian vegetation can increase water temperature and deteriorate water quality (Osborne and Kovacic, 1993; Stadtmüller, 1994). Deforestation and degradation of forest cover and riparian buffer strips have negative effects on water quality and water yield in the catchment; moreover, mismanagement of water resources further aggravates this situation.

Valid universal declarations of the impacts of the forest cover on water resources for different reasons are difficult to elaborate: these impacts depend on a set of natural factors (such as climate, soil type, geology, topography, microclimatic conditions, forest health, forest composition, basin size, *etc.*) and socioeconomic factors, such as economic capacity and awareness of farmers, management practices, and infrastructure development (Kiersch and Tognetti, 2002). Currently, basin-scale research is still needed to advance our understanding of forest impact and land use on hydrology (Andréassian, 2004). Regarding the study of water quality, a basin-scale approach was proposed by the European Community (EU, 2003), based on the concept "pressure, pathway, receptor", which has been used in some recent studies (Pacheco et al., 2015; Santos et al., 2015b). The objective of this research is to bring knowledge and better understand the relationships of forest cover, riparian buffer strips and other social catchment features with water quality and water yield in the upper Grijalva River basin in the Mexico and Guatemala border. With this in mind we elaborate on the following research questions: which season of the year presents better water quality? How are forest cover and riparian buffer strips related to water quality and water yield? How much influence do social factors have in water quality and yield?

2. Materials and methods

2.1. Study sites

The research was conducted in the upper Grijalva River basin in the Mexico and Guatemala border (Fig. 1). Annual average precipitation in the study area is 1,050 mm, with a marked rainy season from May to October, according to Motozintla de Mendoza and Buenos Aires weather stations

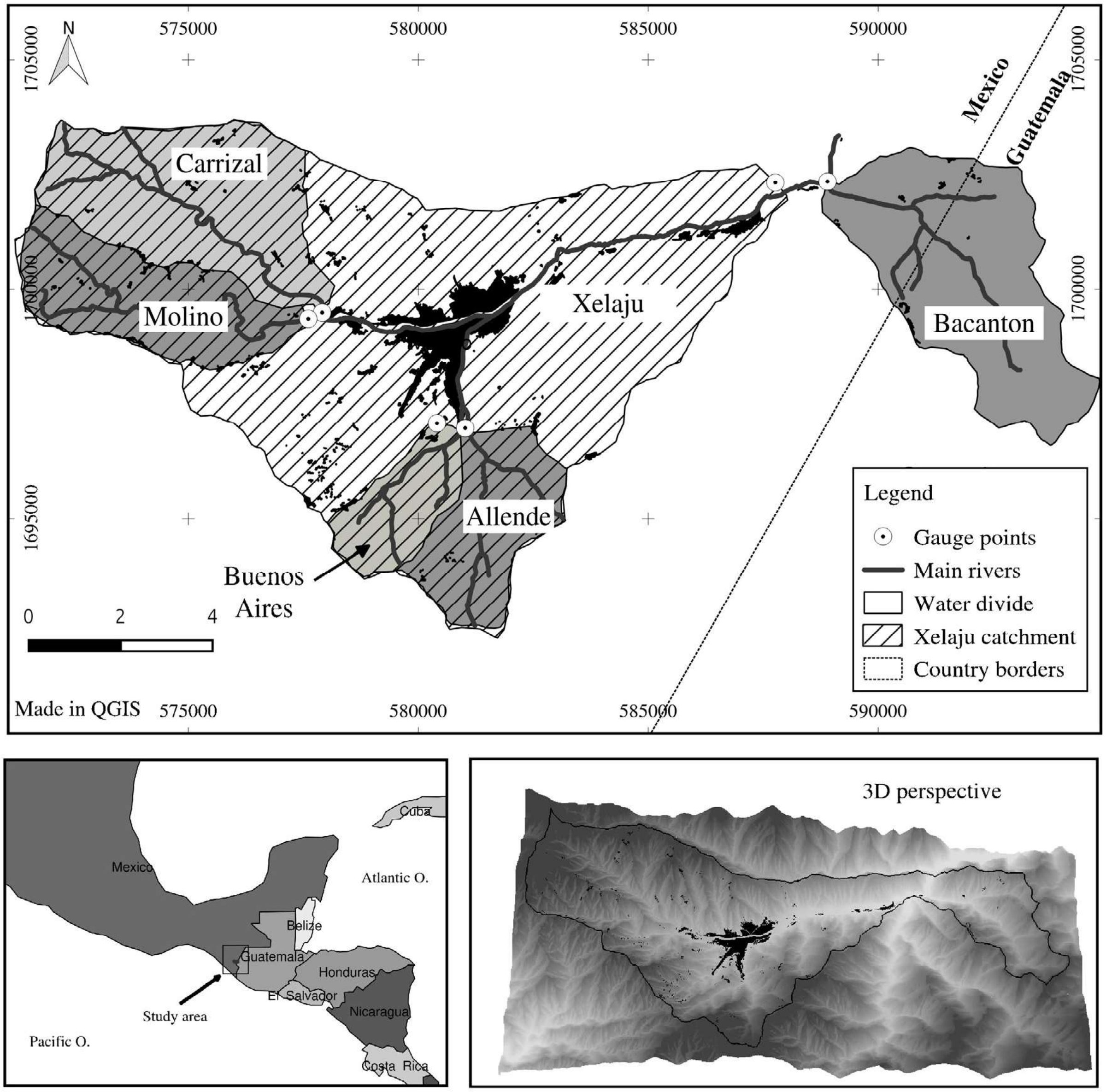

Fig. 1. Study area. Water quality and base flows were estimated in gauge points of the Xelaju and Bacanton river catchments as well as in sub-catchments of Xelaju river: Allende, Buenos Aires, Molino and Carrizal.

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	1498	1751	2321	33 068
Land area (ha)	884	532	1146	1693	1968	9728
Population density (No. people/ha)	0.64	0.34	1.31	1.03	1.18	3.40

(CONAGUA, 2013). Elevation varies from 1050 to 2560 m, while the slope is 7.14% (49°) to 20.74% (11–12°) (INEGI, 2013).

The study area included 120 km^2 delimited by the water-divide of the Xelaju and Bacanton river catchments. We focused on this area as it had been part of the Grijalva River Project carried out by *El Colegio de la Frontera Sur* during 2012 and 2013. We measured base flows and water quality parameters at the gauge points of these rivers as well as in four sub-catchments of the Xelaju river: Allende, Buenos Aires, Molino, and Carrizal. Xelaju river catchment is located entirely in Mexico; Bacanton river catchment includes Guatemalan territory upstream as well as Mexican territories downstream (Fig. 1). Data of population, population density and area of each catchment are provided in Table 1 (source: Laino-Guanes et al., 2014).

2.1.1. Land use and vegetation types

Geospatial vector data of vegetation classes and land uses was obtained from the Grijalva River Project, however, original categories were reclassified using forest inventory data by Ramírez-Marcial et al. (2014) together with supervised classification from the same project carried out in 2011–2012. Guatemala vegetation cover was obtained from interpretation of satellite imagery available in 'Open Layers' plugin in QGIS with field supervision. Forests in the study area have been affected by natural and anthropogenic disturbances, and partially transformed to agricultural land. Remnants of these forests are severely disturbed and dominated by pine and oak species at the canopy level (*Pinus* and *Quercus*), also, smaller areas of deciduous and montane cloud forest can be found within the catchments (Table 2).

2.1.2. Riparian buffer strips

Riparian protection categories were assigned using QGIS standard geoprocessing tools, replicating methodology by Ramírez-Marcial et al. (2014) and completing land use information for the Guatemalan side of the Bacanton watershed which was not included in the mentioned work. The method (modified from Dose, 2009) is based on a re-categorization of land use and vegetation types into three protection categories along the river network, grouping natural occurring vegetation, wetlands and river beds as 'well protected', and considering other land uses such as agricultural activities or urban settlements as 'unprotected', with some categories such as open shrublands or disperse trees falling in an intermediate category (Table 3). Although for this study we focused on riparian buffer strips, it is acknowledged that protection of water bodies and rivers cannot solely be accomplished by riparian vegetation and should consider other factors such as slope, stone walls sedimentation or terraces (Panagos et al., 2015).

2.2. Water quality and base flows

Nine sampling campaigns were conducted between August 2011 and April 2013, four of them in the rainy season and five in the dry season. Grab samples were collected from gauge points of the six catchments under base flow conditions. A total of 48 water samples and 54 base flow measurements were collected for the study. Samples were tested for temperature, pH, dissolved oxygen (DO), total nitrogen (TN), nitrates, nitrites, total phosphorus (TP), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total dissolved solids (TDS), total suspended solids (TSS) and total coliforms.

Table 2

Land-use and vegetation types of studied catchments.

Land-use/vegetation types (%)	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
Settlements	0.3	0.6	0.8	0.6	0.3	3.8

Table 3
Percentage of protection in 100 m riparian buffer strips.

Riparian buffer strips (% of protection)	Allende river	Buenos Aires river	Molino river	Carrizal river	Bacanton river	Xelaju river
Unprotected	22	2	36	37	29	34
Medium protection	31	18	45	22	7	28
Well protected	47	80	19	41	64	38

Water temperature, pH and DO were measured *in situ* by an electrochemical method (APHA, 1998) for the first two parameters, and using a field meter equipped with a DO electrode with chemiluminescent membrane in the case of the latter parameter (Alvarez-Cobelas et al., 2008; Anbumozhi et al., 2005; Campana and Tucci, 2001; Jiménez-Cisneros, 2001). All other parameters were analyzed in the laboratory. Samples were maintained in ice coolers and the approximate time of delivery to the laboratory was less than 24 h. Nitrogen and phosphorus were determined according to HACH's methods and reagents (HACH, 2005). TN was tested according to HACH's 10071 persulphate digestion method, nitrate was determined by the cadmium reduction method (HACH 8039) adapted from the standard methods for the examination of water and wastewater (APHA, 1998), nitrite concentration was measured by the diazotization method (HACH 8507) approved by EPA and described in Mexican Norms (NMX-AA-099-SCFI, 2006) and, finally, TP was tested by the molybdovanadate method (HACH 10127).

COD was measured through the spectrophotometric method described in Mexican norms (NMX-AA-030-SCFI, 2001), and BOD was measured following volumetric method described in Mexican norms (NMX-AA-028-SCFI, 2001). TDS and TSS were analyzed by the gravimetric method described in Mexican norms (NMX-AA-034-SCFI, 2001), and total coliforms were measured by the most probable number (MPN) microbiological method described in Mexican norms (NMX-AA-42, 1987). At each sampling site and at the time of water sample collection, base flows were calculated from measurements of depth and flow velocity. Flow velocity was measured with a flow probe (FP101 Global Flow Probe) following the user's manual recommendations (Global Water, 2004). The float method was applied in cases where rivers were too shallow or with a high content of stones, according to Villón Bejar (2002). A cross section of the river stream was completed for each sampling site at each sampling time, with depth measurements at every 20 cm; area of each cross section was estimated using Autocad software. Direct runoff was not considered in this study. Water yield was calculated on base flow conditions. Water yield in this study corresponds to measured flow in each gauge point divided by total area of the catchment, as to express water production per unit of area.

3. Data analysis

Statistical analyses were carried out using InfoStat Statistical Package (Di Rienzo et al., 2013):

(1) Principal components analysis (PCA) was performed to study the relationship between water quality parameters and water yield in the catchments during the sampling period (August 2011 to April 2013). Biplot obtained by PCA considered year effect, each catchment effect and seasons effect. Involved variables were water yield and water quality: temperature, pH, TDS, TSS, DO, COD, BOD, TN, nitrate, nitrite, TP and total coliforms.

(2) Analysis of variance (ANOVA) was performed using linear mixed models to evaluate water quality with season and river treated as fixed effects and year as random effect, because of the year effect is not reproducible. For this analysis, only data from rivers that maintained their flow throughout the year were selected to make comparisons between seasons, considering that two of the studied rivers did not have flow during dry season. Fisher LSD was used to find mean differences when null hypothesis was rejected.

(3) ANOVA using linear mixed models was performed to evaluate water yield using river and season as fixed effects and year as random effect. Afterwards, catchments were classified into two groups: catchments with more than 50% of forest cover; and catchments with less than 50% of forest cover; ANOVA was used in order to analyze water yield with forest cover in dry and wet seasons in a broader manner. Fisher LSD was used to find mean differences when null hypothesis was rejected.

(4) Pearson's pair-wise correlations were calculated in order to identify relationships ($p < 0.05$) between hydrological and social catchments features. Considered hydrological and social variables included water yield, water quality parameters, water nutrient concentration, level of protection of riparian buffer strips, population density and urban areas.

(5) Partial least squares (PLS) regression was used to evaluate associations between water quality, water yield, population density and levels of protection of riparian buffer strips. PLS is a powerful and effective method to handle high dimensional component to the data set along with the multi-colinearity of the variables (Abdi, 2010). To show these associations with each catchment a triplot graphic was generated using protection levels of riparian buffer strips as predictor variables and parameters of water quality, water yield and population density as response variables.

4. Results and discussion

4.1. Water quality and water yield in wet and dry seasons

Results from physical, geochemical and biological parameters of water quality are presented in Table A1 in the appendix. According to PCA, the Xelaju River

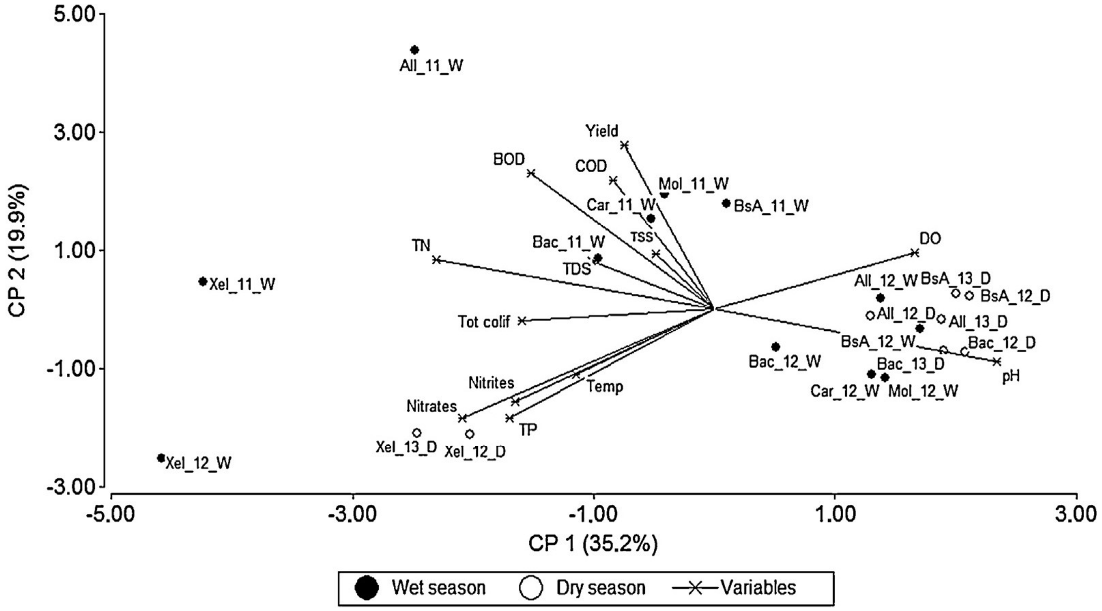

Fig. 2. Bi-plot obtained by principal components analysis (PCA) based on effect of year (11 = 2011, 12 = 2012 and 13 = 2013) for each catchment (Xel = Xelaju, All = Allende, BsA = Buenos Aires, Mol = Molino, Car = Carrizal and Bac = Bacanton) in both wet (letter W, filled dots) and dry (letter D, white dots) seasons. The variables shown as vectors are temperature (Temp), pH, total dissolved solids (TDS), total suspended solids (TSS), dissolved oxygen (DO), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), nitrate, nitrite, total phosphorus (TP), total coliforms (Tot colif) and water yield (Yield).

catchment differed widely from other catchments (Fig. 2). The differences are mainly due to the water yield with greater nutrient concentrations (TN, TP, nitrites and nitrates) and higher total coliform levels and temperature. The Allende River catchment produced the highest water yield with greater concentrations of BOD and COD in wet season. Allende and Buenos Aires produced water with higher levels of DO. PCA explained 55.1% of data variation in the first two principal components.

Statistical differences ($p < 0.05$) in water quality between seasons of the year were found for half of measured parameters. In general, better water quality was observed during the dry season in rivers that maintained flow during the entire year. That is, higher values of DO and lower levels of TDS, TSS, TP, COD and temperature were observed in that period. BOD did not show significant statistical differences ($p = 0.0941$), possibly due to high standard error for wet (± 2.01) and dry (± 1.74) seasons for this variable; however, in wet season the average value of BOD was double than the average value in dry season. Presence of total coliforms did not show significant statistical differences ($p = 0.7723$), however in both wet and dry seasons the values were extremely high, meaning water contamination both in wet and dry seasons (Table 4).

In the rainy season, when water yield increases, generally better water quality is expected due to highest dilution of pollutant (Marsalek et al., 2008; Nilsson and Malm Renöfält, 2008; Olías et al., 2004; Van Vliet and Zwolsman, 2008). However, our results differ with this assumption. While some studies reported better water quality in the wet season (Ombaka et al., 2013; Yusuf et al., 2008), other authors found better water quality in the dry season like us (Anhwange et al., 2012; Castillo et al., 2013). However, in all cases there are exceptions and some water quality parameters responded in different way. The lower water quality in the rainy season could be caused from the influence of steep slopes present in the study area, increasing soil erosion and sediment runoff, which pollute water altering its physical and chemical parameters (Kiersch, 2000). Studies carried out in Portugal showed that larger nutrient export was mostly related to big soil losses triggered by intense rainfall events (Pacheco et al., 2015; Santos et al., 2015b).

4.2. Influence of forest cover on water yield in wet and dry seasons

Water yield (l/min/ha) and forest cover (% of the area) of the catchments in dry and wet seasons are shown in Fig. 3. Data is reported in appendix (Table A2).

Table 4
Season effect on water quality determined through ANOVA using general mixed linear models. Values are in mg/l, except pH (pH units), temperature (°C) and total coliforms (MPN/100 ml). Means sharing a same letter are not significantly different ($p > 0.05$).

Parameter	Wet season	Dry season	p-value
DO	7.04 B	7.45 A	0.0213
TDS	363 A	193 B	0.0007
TSS	219 A	189 B	0.0356
TP	1.05 A	0.69 B	0.0009
COD	60.53 A	28.00 B	0.0474
Temp	23.82 A	22.12 B	0.0197
BOD	10.26 A	5.50 A	0.0941
TN	1.84 A	1.24 A	0.1065
Nitrates	0.64 A	0.50 A	0.3931
Nitrites	0.02 A	0.03 A	0.8209
Tot colif	117 744 A	105 340 A	0.7723
pH	8.30 A	8.38 A	0.1165

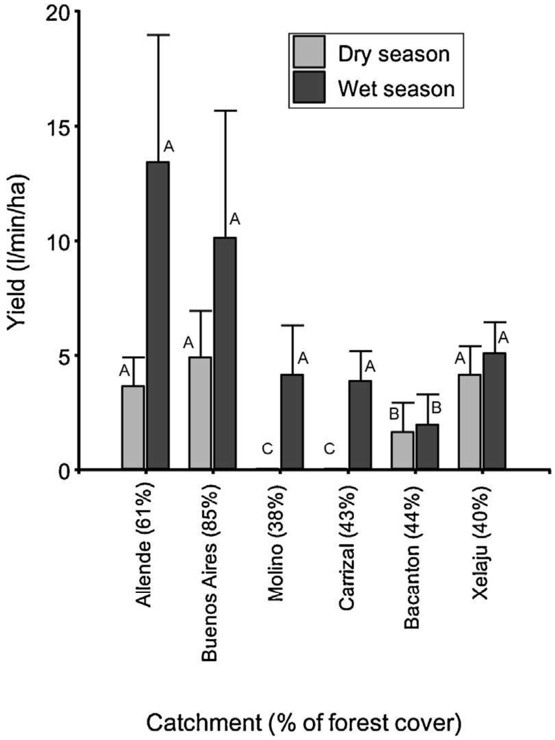

Fig. 3. Analysis of variance for water yield (l/min/ha) comparing mean values of six catchments in both dry and wet seasons using linear mixed models with season and river treated as fixed effects and year as random effect. Means sharing a same letter are not significantly different (Fisher LSD, $p > 0.05$). Percentage of forest cover is shown next to each catchment name.

No statistical differences in water yield were found neither between catchments nor between wet and dry season (letter A), except for: (1) Bacanton river catchment that showed a lower yield value (letter B), and (2) Molino and Carrizal river catchments, in which the flow dried completely during dry season (letter C). Excepting for Molino and Carrizal, rivers of the other four catchments maintained flow during the entire year, even though, two of them are subject to extraction and represent the main sources of water for downstream populations (Allende and Buenos Aires).

We do not have enough evidence to explain the difference in water yield of the Bacanton river catchment which produced less water than the others (except in the dry season), even though it has the same (or more) area of forest cover. However, we can mention two features of the Bacanton river catchment that could explain the differences: (1) Allende, Buenos Aires, Molino and Carrizal are sub-catchments of the Xelaju river catchment, hence all of them have the same microclimatic characteristics, but there are not shared with Bacanton catchment (Fig. 1). For this research we used data of two weather stations located in Xelaju river catchment, and the closest available to the Bacanton river catchment; however, it could occur that local weather variations between the two catchments are influencing flow regime; (2) the forest cover of the Bacanton river catchment is composed mainly of deciduous tree species (46%) and is different to that of the other catchments which have more pine-oak and pine forests, and less deciduous forest influencing total forest cover: Buenos Aires (0%), Allende (1.63%), Carrizal (4.45%), Molino (21.26%), and Xelaju (28.46%) of deciduous forest (Table 2). Although we did not analyze the effect of forest types, this fact highlights the need to include research with descriptors such as tree species in each type of forest (Andréassian, 2004). In addition, runoff potentiality (runoff coefficient and curve number) was not analyzed in this study, which could explain the runoff variations among the catchments.

Bacanton catchment did not present statistical differences in water yield between dry and wet seasons, nonetheless showing the smallest difference of all studied catchments (Fig. 3). According to Zingari and Achouri (2007), forested catchments (with healthy forests) moderate flow variations along the whole year, compared to other land uses. Presumptively, a distinct level of health or degradation of deciduous forest of the Bacanton river catchment could explain such difference.

After classifying the catchments into two groups, it was found that catchments with more than 50% of forest cover generate higher water yield than catchments with less than 50% of forest cover ($p = 0.0165$). As expected, all catchments produce higher water yield in the rainy season ($p = 0.0136$). In the dry season, two of the less forested catchments dried completely, these were the only two rivers that showed intermittent flow in our study area. Further research is needed to understand the role of forests, forest type and forest health, in the reduction of flow in the dry season.

4.3. Influence of land cover, vegetation types and riparian buffer strip on water quality and water yield

Water quality parameters most associated with land cover were dissolved oxygen (DO) and water temperature (Temp). Catchments with more forest cover had water with higher concentration of DO ($r = 0.60$, $p < 0.0001$) and lower temperature ($r = -0.80$, $p < 0.0001$). Water with lower concentration of DO came from catchments with larger areas of open shrubland ($r = -0.60$, $p < 0.0001$) and bare ground ($r = -0.68$, $p < 0.0001$). Higher water temperatures were observed in catchments with higher areas of open shrubland ($r = 0.58$, $p < 0.0001$), grassland ($r = 0.62$, $p < 0.0001$), agricultural land ($r = 0.75$, $p < 0.0001$) and bare ground ($r = 0.69$, $p < 0.0001$). According to Osborne and Kovacic (1993) and Stadtmüller (1994) riparian vegetation has an effect on water temperature, and the removal of riparian vegetation can cause an increase in temperature causing water thermal pollution. This is similar to what is reported in recent studies, which show a significant impact of land use on water quality, emphasizing the key role of riparian vegetation in the conservation of aquatic ecosystems (Valle Junior et al., 2015), concluding that the maintenance of good conditions of vegetation, adjacent to rivers, are an asset in improving water quality. Our results show that catchments with unprotected riparian buffer strips (100 m on each side of the river) presented higher water temperature ($r = 0.75$, $p < 0.0001$) and lower DO ($r = -0.60$, $p < 0.0001$). In the same way, a study carried out in New Zealand showed that riparian restoration had a positive effect on water quality in terms of increasing DO (Collins et al., 2013).

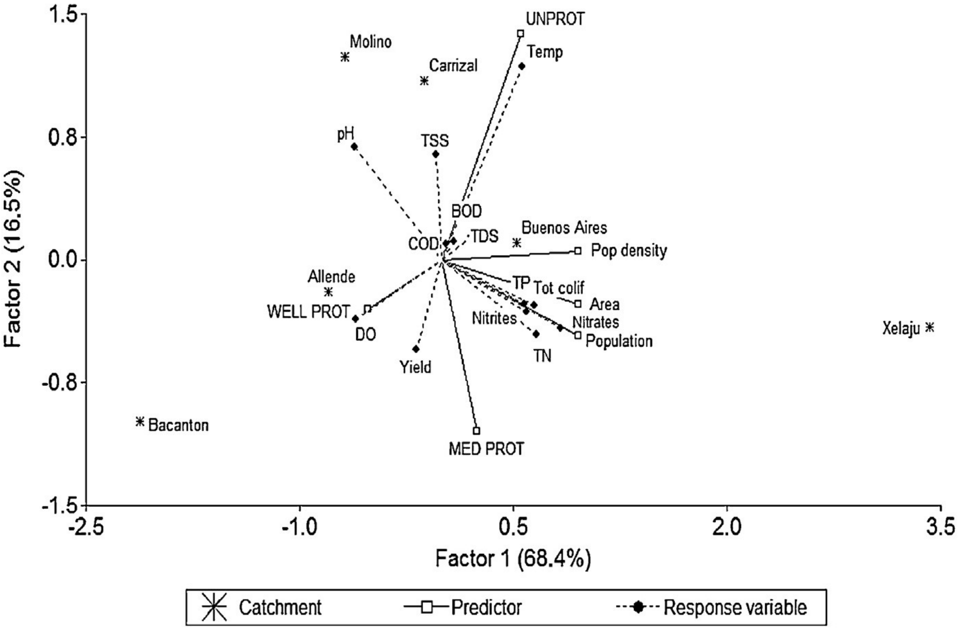

Fig. 4. Partial least squares (PLS) regression showing associations between each catchment with protection levels of riparian buffer strips (predictor variables) and variables of water quality, water yield and population density (response variables). Predictor variables show the protection of riparian buffer strips described in Table 3: WELL PROT = well protected, MED PROT = medium protection and UNPROT = non-protected.

Results of PLS analysis suggested differences among Xelaju river and the other catchments (Fig. 4). Higher nutrient levels (nitrogen, phosphorus, nitrates and nitrites) and total coliforms were associated with the largest urban area, population density and unprotected riparian buffer strips of the Xelaju river catchment. Allende and Bacanton river catchments were associated with well protected riparian buffer strips and higher levels of DO and water yield.

Molino and Carrizal river catchments were associated with unprotected riparian buffer strips, highest temperature and TSS levels, and lowest water yield. PLS analysis explained 84.9% of data variation in the first two factors.

4.4. Human pressure on catchments

Our results show that catchments with higher population density and larger urban areas generated water with higher total coliform levels ($r = 0.57$, $p = 0.0001$ and $r = 0.59$, $p = 0.0001$ respectively). In addition, nutrient concentrations (nitrogen, phosphorus, nitrates and nitrites) were also higher (Table 5). Residential land uses play important roles in influencing water quality of adjacent aquatic systems, by generating point and non-point source pollutants, and by increasing the impervious area (Somura et al., 2012). Catchments with large urban lots or impervious surfaces have elevated levels of nutrients (Schoonover et al., 2005) and suspended solids (Ahearn et al., 2005; Sliva and Williams, 2001).

Table 5
Relationship between nutrient concentrations in water, population density and settlement area (Pearson's correlations $p < 0.05$).

Nutrient/variables relationship	*r*	*p*-value
TN/Population density	0.59	0.0001
TN/Settlements	0.63	<0.0001
Nitrates/Population density	0.78	<0.0001
Nitrates/Settlements	0.81	<0.0001
Nitrites/Population density	0.55	0.0002
Nitrites/Settlements	0.58	0.0001
TP/Population density	0.68	<0.0001
TP/Settlements	0.71	<0.0001

Results of water quality analysis and the exponential increase of total coliforms in water, after passing through Motozintla de Mendoza and Mazapa de Madero towns (gauge point of catchment 6, Fig. 1), show that the population density of these towns and the lack of treatment of wastewater are polluting the Xelaju river, highlighting the need of sewage treatment plants in order to prevent potential health problems in populations downstream (DMA, 2000; Laino-Guanes et al., 2014).

The availability of fresh water in rivers is one of the major issues facing human populations especially in developing countries (Vialle et al., 2011). Decreased water yield and deteriorated water quality in the study area are not only related to reduction and degradation of forest cover and riparian buffer strips, but also to inadequate management of water resources.

5. Conclusions

Water quality was better during dry season, with higher values of DO and lower levels of TDS, TSS, TP, COD and temperature. Catchments with higher forest cover produced water with higher concentration of DO and lower temperature. Well protected riparian buffer strips were associated with production of water with higher levels of DO and highest water yield. Rivers of more forested catchments (Allende and Buenos Aires) maintained flow during the entire year; even though they are the main sources of water for the population. Two of the less forested catchments (Molino and Carrizal) dried completely during dry season; these were the only rivers that showed intermittent flow in our study area. Decreased water yield and deteriorated water quality in the study area are not only related to reduction and degradation of forest cover and riparian buffer strips, but also to inadequate management of water resources. Catchments with higher population density and larger urban areas generated water with higher total coliform levels and higher nutrient concentrations.

Conflict of interest

Authors declare that there is no conflict of interest in this article. This work is a portion of a doctoral research project financed by the *Consejo Nacional de Ciencia y Tecnología* (CONACyT) of Mexico.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Appendix

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecohyd.2015.12.002.

Table A1
Mean (±S.E.) of physical, chemical and biological parameters recorded in dry and wet seasons in six catchments. Values are in mg/l, except pH (pH units), temperature (°C) and total coliforms (MPN/100 ml). Temp = temperature, DO = dissolved oxygen, COD = chemical oxygen demand, BOD = biochemical oxygen demand, TN = total nitrogen, TP = total phosphorus, TDS = total dissolved solids, TSS = total suspended solids, Tot colif = total coliforms, and ND = no data (rivers without flow during dry season).

Catchment	Temp	DO	pH	COD	BOD	TN	Nitrate	Nitrite	TP	TDS	TSS	Tot colif
Dry season												
Allende	19.0 ± 1.4	7.5 ± 0.2	8.4 ± 0.007	31.5 ± 13.2	6.5 ± 3.1	0.9 ± 0.3	0.3 ± 0.07	0.024 ± 0.021	0.5 ± 0.0	89.7 ± 49	3.3 ± 2.1	1,270 ± 653
Buenos Aires	18.0 ± 1.2	7.7 ± 0.2	8.5 ± 0.06	37.2 ± 16.3	6.3 ± 3.2	0.3 ± 0.1	0.1 ± 0.05	0.003 ± 0.0	0.6 ± 0.1	128.9 ± 79	2.0 ± 1.1	1645 ± 998
Molino	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Carrizal	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bacanton	26.2 ± 0.6	7.6 ± 0.2	8.6 ± 0.08	16.3 ± 8.9	3.8 ± 1.5	0.3 ± 0.1	0.1 ± 0.06	0.004 ± 0.001	0.6 ± 0.1	182.0 ± 108	4.3 ± 2.5	4615 ± 2290
Xelaju	25.4 ± 0.3	6.9 ± 0.3	8.2 ± 0.04	27.1 ± 17.8	5.5 ± 1.8	2.2 ± 0.4	1.4 ± 0.17	0.087 ± 0.055	1.3 ± 0.3	208.3 ± 123	1.8 ± 0.8	160,299 ± 101 587
Wet season												
Allende	19.2 ± 0.9	7.6 ± 0.2	8.3 ± 0.1	99 ± 37.8	11 ± 8.0	1.5 ± 1.1	0.3 ± 0.13	0.004 ± 0.003	0.9 ± 0.1	243.5 ± 77	31.1 ± 9.3	1239 ± 405
Buenos Aires	19.6 ± 0.8	7.5 ± 0.1	8.4 ± 0.08	22 ± 8.7	5.4 ± 2.3	0.9 ± 0.2	0.2 ± 0.02	0.005 ± 0.003	0.8 ± 0.1	269.3 ± 49	38.5 ± 19.4	3926 ± 2382
Molino	25.8 ± 0.8	6.8 ± 0.1	8.4 ± 0.1	92.3 ± 85.4	3.8 ± 1.7	0.7 ± 0.2	0.3 ± 0.06	0.003 ± 0.001	0.6 ± 0.0	160.1 ± 34	51.9 ± 45.5	6462 ± 5847
Carrizal	27.7 ± 0.5	6.5 ± 0.0	8.5 ± 0.06	40.3 ± 36.8	10 ± 8.0	0.7 ± 0.3	0.2 ± 0.08	0.004 ± 0.003	0.6 ± 0.1	284.4 ± 125	236.8 ± 227.7	1077 ± 454
Bacanton	29.2 ± 1.1	6.7 ± 0.2	8.5 ± 0.1	66.1 ± 33.3	12.4 ± 6.1	0.8 ± 0.3	0.3 ± 0.05	0.004 ± 0.002	1.0 ± 0.1	267.6 ± 69	548.8 ± 484.4	9955 ± 5101
Xelaju	27.3 ± 0.9	6.4 ± 0.2	8.0 ± 0.04	55 ± 28.0	12.2 ± 5.9	3.5 ± 0.9	1.8 ± 0.61	0.088 ± 0.055	1.5 ± 0.3	359.3 ± 79	71.7 ± 59.5	428,105 ± 243,415

Table A2

Mean (±S.E.) of water yield (l/min/ha) recorded in wet and dry seasons in six catchments.

Catchment	Water yield (l/min/ha)	
	Wet season	Dry season
Allende	13.4 ± 5.5	3.6 ± 1.3
Buenos Aires	10.1 ± 5.5	4.9 ± 2.0
Molino	4.1 ± 2.2	0
Carrizal	3.9 ± 1.3	0
Bacanton	1.9 ± 1.3	1.6 ± 1.3
Xelaju	5.1 ± 1.3	4.1 ± 1.3

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