Exploring Hydrologic Connections between Tropical Mountain Wetlands and Glacier Recession in Peru's Cordillera Blanca

Abstract. Receding mountain glaciers affect the hydrology of downslope ecosystems with consequences for drinking water, agriculture, and hydropower production. Here we combined land cover derived from satellite imagery and other environmental data from the northern Peruvian Andes into a first differencing regression model to assess wetland hydrologic connectivity. Wetland area was considered the response variable and a variety of land cover, climatic, and stream discharge explanatory variables were tested to evaluate effects of possible hydrologic connectivity. The results indicate that there were two primary spatial driving forces of wetland change in Peru's Cordillera Blanca from 1987 to 1995: 1) loss in glacier area was associated with increased wetland area, controlling for other factors; while 2) an increase in mean annual stream discharge in the previous 12 months increased wetland area. The general approach we used expands the ways that connectivity between landscape changes and hydrologic and ecosystem processes can be assessed.

Keywords: land change science, climate change, hydrology, tropical glaciers, mountain wetlands

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1. Introduction

Landscape change can result from shifting hydrological processes and, in turn, feedbacks through altered evapotranspiration, runoff, and water storage can further influence landscape arrangement and composition. Landscape changes detected by satellite observations provide insights into the hydrologic connectivity that characterizes these processes, although quantifying the effects is complicated by high natural variability, typically unmeasured groundwater interconnections, and incomplete data archives (DeFries & Eshleman, 2004; Wohl et al., 2012). In this research, we adapt an econometric model to examine the influence of glacier retreat on downslope wetland ecosystems. To do this, we utilized an historic stream discharge dataset for selected Santa River watersheds in the Cordillera Blanca of northern Peru and compared it to land cover change derived from satellite imagery. The general approach can be adapted to study many other situations where the relationship between hydrologic connectivity and environmental drivers of change is in need of assessment (e.g. Ponette-González et al., 2014).

In joining econometric modeling with spatial categorical data, the explanatory variables can be conceived of as spatial driving forces, with ancillary datasets representing variables such as precipitation, evapotranspiration, or topography that can further specify the model (Chowdhury, 2006). Response variables can similarly be extracted from spatial categorical data derived from remotely-sensed imagery. Multiple logistic regression is often used (Cui, Gao, Zhou, & Mu, 2014; Mertens & Lambin, 2000), which provides a probability estimate of the effect of the explanatory variables on the response variable (Wooldridge, 2009). Another technique involves panel data and fixed effects regression (Andreß, Golsch, & Schmidt, 2012), which relies on a simple design: make each observation its own control. In this case, for each watershed we can estimate the effects of explanatory variables and control for unobserved

variables. This is useful in studies where a non-experimental design is the only available strategy to evaluate interconnections. The response variable must be measured on two occasions at a minimum and the measurements must be directly comparable over time; additionally, the explanatory variables must exhibit variation across time (Allison, 2009). In contrast to multiple logistic regression that measures a probability response for change from one land cover to another, fixed effects regression generates an estimate of the relative effect of an explanatory variable over time, thus explicitly estimating how changes in the explanatory variables affect the response variable temporally (Wooldridge, 2009); doing so eliminates time-constant effects, both observed and unobserved. When two time periods are used, the technique is referred to as first differencing (Wooldridge, 2009).

Here we utilize the changes in wetland area as a way to evaluate hydrologic connectivity as affected by the glaciers themselves, and by other hydrologic and climatologic variables. Like many glaciated mountains nowadays, ice cover in the Cordillera Blanca is decreasing (Kaser, 1999; Rabatel et al., 2013; Thompson et al., 2006). Permanent ice cover declined from 723 km² in 1970 (Kaser, Ames, & Zamora, 1990) to 482 km² by 2010 (Burns & Nolin, 2014). Ice loss in the high Andes is associated with multiple social and biophysical consequences including changing water supplies for human uses as well as ecosystem integrity (Bradley et al. 2006), a coupled relationship that has been observed globally (Viviroli et al. 2007). The effects on stream discharge are often region-specific based on climatological differences. There is, however, a widely accepted conceptual model that broadly describes the impact of glacier recession on stream discharge. Introduced by Braun et al. (2000), the model has been reproduced in a number of studies with each contributing slight variations (Hock, Jansson, & Braun, 2005; Jansson, Hock, & Schneider, 2003; Moore et al., 2009; Nolin, Phillippe, Jefferson, & Lewis, 2010; Rees

& Collins, 2006). More recently conceptualized as “peak water” by Carey et al. (2014), the model characterizes the impact of glacier retreat on surface hydrology by an initial increase in annual stream discharge during the early stages of deglaciation, followed by a decline in stream discharge as the glacier volume becomes too small to sustain flows. In addition to change in mean annual discharge, the hydrological transformation is characterized by an increase in discharge variability (Collins, 2008).

Recently, Baraer et al. (2012) have explored the peak water concept for the specific case of the Cordillera Blanca. Their study suggests that most of the streams in the Cordillera Blanca have undergone a decline in annual and dry season stream discharge since the 1980s that is related to glacier retreat. In addition to decreasing mean annual discharge, an increase in the annual variability of flows was observed. The researchers predicted that when glaciers lose their hydrological influence, yearly stream discharge should stabilize at a slightly lower level than earlier and dry season discharge is anticipated to be lower. Baraer et al. (2012) corroborated conclusions from previous studies focusing on the Cordillera Blanca: Juen et al. (2007) and Vuille et al. (2008) showed that reductions in glacier area may result in no major net change in annual total runoff, but seasonal variation should increase. In 2005, Pouyaud et al. (2005) projected a similar stream discharge evolution, but in a different timeframe.

Much of the high mountain landscapes within the Cordillera Blanca are within the boundary of Huascarán National Park where valley peatlands and wet meadows (together referred to herein as wetlands) form patches that are changing spatially. A case study from one valley, Quilcayhuanca, evaluated changes from 2000 to 2011. Over the 11-year interval, wetlands in Quilcayhuanca became smaller and more fragmented (Bury et al., 2013). Other research performed at the scale of the park (all valleys inside the park) found that wetland

spatiotemporal change trends are nonlinear with wetlands increasing in area from 1987 to 1999, then decreasing in area from 1999 to 2010 (Polk, 2016). Relevant to this study is that in 1987, wetland occupied 12,402 hectares and by 1995, wetland had increased to 13,858 hectares, an 11.7% increase over 8 years (Polk, 2016). The wetlands receive input from groundwater, precipitation, and surface water flows, while they also contribute to aquifers and streamflow (Gordon et al., 2015; Maldonado Fonkén, 2015). Outflows from peatlands are seasonally variable, increasing during rainy periods and decreasing in the dry season when evapotranspiration is higher and inputs are lower (Rydin & Jeglum, 2013).

We explored the possible statistical relationships between area of wetlands and shifting hydrologic processes by testing seven hypotheses (Table 1). Because wetlands are spatially proximal to glaciers in the study area (Figure 1), change in glacier area should be associated with change in wetland area (H1). In most Cordillera Blanca watersheds, proglacial lakes dammed by moraines (or engineered impoundments) store glacier meltwater. Ice loss is associated with increasing lake surface area and volume (Emmer, Vilimek, Klimeš, & Cochachin, 2014), so wetlands could be changing as a statistical function of both glaciers and lakes (H2). Baraer et al. (2012) showed that the Santa River discharge is decreasing while variability is increasing as glaciers recede, so changes in discharge and glacier area could be used jointly to estimate wetland area change (H3). By combining those three hypotheses, changes in glacier area, lake area, and discharge can be used as explanatory variables (H4). Some wetlands in the Peruvian Andes are thought to be groundwater-supported fens (e.g. Cooper et al., 2010), but in the study area wetlands may be maintained only by precipitation (bogs). As such, H5 introduces a lagged precipitation variable in place of lake area to address this possibility, and maintains the relationship between glacier area and discharge; a lagged variable is used because some water

held in wetlands may be stored from prior rainy seasons, although the residence time is unknown (Gordon et al., 2015). In H6, we include four variables, changes in glacier area, discharge, lake area, and precipitation, to estimate wetland change. Finally, it may be that changing discharge and precipitation may alone predict wetland change (H7), as glaciers recede, assuming that the influence of meltwater will diminish and precipitation will be the key driver of streamflow (Baraer et al., 2012; Mark & Seltzer, 2003).

Table 1. Hypotheses exploring the relationships among changing wetlands and other variables.

- H1** Glacier recession has an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$.
- H2** Glacier recession and changing lake area have an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$ and $\Delta\beta_{\text{Lake_area}} \neq 0$.
- H3** Glacier recession and decreased discharge have an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$ and $\Delta\beta_{\text{discharge}} \neq 0$.
- H4** Glacier recession, decreased discharge, and change in lake area have an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$, $\Delta\beta_{\text{discharge}} \neq 0$, $\Delta\beta_{\text{Lake_area}} \neq 0$.
- H5** Glacier recession, decreased discharge, and change in prior precipitation have an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$, $\Delta\beta_{\text{discharge}} \neq 0$, $\Delta\beta_{\text{ppt}} \neq 0$.
- H6** Glacier recession, decreased discharge, change in lake area, and change in prior precipitation have an effect on wetland area; $\Delta\beta_{\text{Glacier_area}} \neq 0$, $\Delta\beta_{\text{discharge}} \neq 0$, $\Delta\beta_{\text{lake_area}} \neq 0$, $\Delta\beta_{\text{ppt}} \neq 0$.
- H7** Decreased discharge and change in prior precipitation have an effect on wetland area; $\Delta\beta_{\text{discharge}} \neq 0$, $\Delta\beta_{\text{ppt}} \neq 0$.

Figure 1. Representations of the possible spatial and hydrologic relationships among changing wetlands and other variables evaluated in this research.

2. Study Area and Methods

2.1. Study Area

The Cordillera Blanca mountain range is located between 8.5 - 10° S and 77° 00' - 77° 50' W and is oriented on a northwest-southeast axis. It is comprised of a series of parallel valleys, each its own watershed in the Santa River basin (Figure 2). The scale of analysis was the watershed level and we evaluated seven watersheds within the Santa River basin. All sample watersheds are located on the west side of the Cordillera Blanca and drain into the Santa River, which flows to the Pacific Ocean. Watersheds on the east side of the divide were not used

because there were no available stream discharge records. The seven watersheds evaluated are representative of the mountain range and span the latitudinal gradient, and vary in size, glacier coverage, and wetland coverage. Wetlands occur at elevations > 3500 m.a.s.l. and are located inside Huascarán National Park, a 3400 km^2 UNESCO Biosphere Reserve (Lipton, 2008, 2014). Based on field observations, wetlands in the study area included both highly organic peatlands and minerogenous wet meadows. Peatlands were dominated by plants including *Plantago tubulosa*, *Eleocharis albibracteata*, and *Oritrophium limnophyllum*, while wet meadows were dominated by *Lachemilla pinnata*, *Agrostis breviculmis*, and *Lucilia kunthiana*.

Figure 2. Study area showing the seven monitored watersheds, their discharge stations, Huascarán National Park, and proximity to the city of Huaraz in northern Peru.

2.2. Data and Analyses

Data completeness, availability, and required variation between the two time periods were the parameters that determined 1987 and 1995 as the time interval studied. Discontinuous hydrological and meteorological observations in the Cordillera Blanca make temporal evaluations challenging and have prompted researchers to scale up effects of glacier recession from relatively small extents such as catchments to regional-scale watersheds (Mark et al., 2005). Near-constant heavy cloud cover during the wet season limits useable imagery captured by optical sensors like Landsat; wet season spatial and ecological dynamics are thus obscured. Spatial change in wetlands, glaciers, and lake areas were derived from classified Landsat TM images acquired on 15 May 1987 and 6 June 1995 (downloaded from <http://glovis.usgs.gov>), chosen because they are years in which all selected data (imagery, climate, and discharge records) are available and gap-free. Methods involved a two-stage process beginning first with extracting the response and explanatory variables (Table 2; pooled summary statistics in Table 3), followed by the first differencing analysis.

Table 2. Variables and their descriptions.

Variable	Symbol	Definition and Ecological Meaning	Unit
RESPONSE			
Wetland Area	WL_area	Area in catchment covered by wetland	ha
EXPLANATORY			
Glacier Area	Glacier_area	Area in watershed covered by snow/ice	ha
Lake Area	Lake_area	Area in watershed covered by lake surface	ha
Mean Annual Discharge	MeanAnnQ	Mean annual discharge from the calendar year coincident with image acquisition year	m ³ /s
6-year Mean Annual Discharge	6MeanAnnQ	Mean annual discharge from the calendar year 6 years prior to image acquisition year (1981, 1989)	m ³ /s
Dry Season Discharge	DryQ	The total discharge from the dry season preceding image acquisition dates (July and August 1986, 1994)	m ³ /s
Wet Season Discharge	WetQ	The total discharge from the wet season preceding image acquisition dates (February and March 1987, 1995)	m ³ /s
Total Annual Precipitation	PrePrior	The total precipitation computed from the 12 months preceding the image acquisition dates	mm
6-year Total Annual Precipitation	6prePrior	The total precipitation computed from the 12 months occurring 6 years preceding image acquisition dates (1981, 1989)	mm
Dry Season Precipitation	preJulyAug	Total precipitation from the dry season preceding image acquisition dates (July and August 1986, 1994)	mm
Wet Season Precipitation	preFebMar	Total precipitation from the wet season preceding image acquisition dates (February and March 1986, 1994)	mm

Table 3. Pooled summary statistics for all variables in 1987 and 1995.
 * represents missing data for La Balsa in 1981. See text for explanation.

Variable	Symbol	Mean	Standard Deviation	Minimum	Maximum
Wetland Area	WL_area	717.13	1303.65	39.96	3745.26
Glacier Area	Glacier_area	7983.51	13,641.12	238.32	43,834.86
Lake Area	Lake_area	335.46	494.39	66.06	1629.72
Mean Annual Discharge	MeanAnnQ	15.17	28.42	1.52	86.31
6-year Mean Annual Discharge	6MeanAnnQ	10.08	22.90	*	89.16
Dry Season Discharge	DryQ	6.00	9.72	0.29	32.06
Wet Season Discharge	WetQ	26.21	50.40	2.89	155.48
Total Annual Precipitation	PrePrior	373.91	49.94	284.90	464.10
6-year Total Annual Precipitation	6PrePrior	718.35	183.12	520.40	990.60
Dry Season Precipitation	PreJulyAug	12.27	21.03	0.50	82.50
Wet Season Precipitation	PreFebMar	142.29	54.28	72.90	222.40

2.2.1. Extracting the Variables

For each date, two Level 1T images (path-row 8-66, 8-67) from the dry season were mosaicked together. Level 1T processing provides systematic, radiometric, and geometric accuracy by using a digital elevation model; image co-registration is consistent and spatial errors are less than one-half of one pixel (Hansen & Loveland, 2012). Images were analyzed independently post-classification, making atmospheric correction unnecessary (Song, Woodcock, Seto, Lenney, & Macomber, 2001). A hybrid supervised-unsupervised image classification was performed (using ERDAS Imagine 2014), a technique that uses all 7 bands in 30 m spatial resolution; band 6 was resampled from 120 m to 30 m (Messina, Crews-Meyer, & Walsh, 2000;

Walsh et al., 2003). The classification technique was selected due to previous good performances in the study region (Kintz, Young, & Crews-Meyer, 2006; Lipton, 2008; Postigo, Young, & Crews, 2008). First, an unsupervised classification (ISODATA) clustered the spectral information into 255 signatures. These signatures were then evaluated using the transform divergence method, removing signatures with low separability. Next, the edited signatures were applied in a supervised classification. To improve the accuracy of difficult-to-classify wetlands, we added a 4-3 band ratio following Ozesmi and Bauer (2002). Lake colors vary widely due to suspended glacial flour in the study area, giving poor classifications; therefore, lakes were digitized manually and modified for each time period based on the GLIMS dataset (<http://www.glims.org>) (Kargel, Leonard, Bishop, Kääb, & Raup, 2014). The final product was a categorical map for each date with seven land cover types: Barren, Puna, Wetland, Snow/Ice, Lake, Shadow, and Cloud; only Wetland, Snow/Ice, and Lake were used in this particular analysis. Accuracy assessments for the land cover classes were within standard norms of over 85% (Congalton & Green, 2008; Khorram, 1999). For 1987, overall accuracy was 89.38% and overall Kappa was 87.52%. For 1995, overall accuracy was 85.4% and overall Kappa was 82.3%.

Precipitation and temperature variables were derived from the Climatic Research Unit dataset, CRU TS 3.10.01 (University of East Anglia Climatic Research Unit, Jones, & Harris, 2013) and downloaded from CGIAR-CSI (<http://www.cgiar-csi.org>). CRU data offers deep temporal resolution from 1901 to 2010 for 0.5° latitude/longitude grid cells. The CRU climate variables were originally synthesized from monthly observations from meteorological stations across the global terrestrial surface, excluding Antarctica (Harris, Jones, Osborn, & Lister, 2014; Mitchell & Jones, 2005); others have used these data for the study region (Urrutia & Vuille,

2009; Vuille et al., 2008) in spite of acknowledgements that the data should be used with caution because there are no inputs from weather stations in Peru and they may overestimate temperature. Data from nearby weather stations were unusable because of discontinuous observations. For 1987 and 1995, four precipitation variables were created that were meant to account for the lagged effect of surface flow and groundwater moving into peatlands (Table 2). For the 12 months preceding the image acquisition dates, total annual precipitation was calculated. We also calculated a 6-year lagged precipitation variable; it is the 12-month total annual precipitation prior to the image acquisition dates in 1981 and 1989. Wet season precipitation is the sum of the two months with historically highest precipitation, February and March (Baraer et al., 2012), preceding the image acquisition dates. Dry season precipitation was calculated from the sum of the two months preceding the image acquisition dates with the historically lowest precipitation, July and August. The temperature variable is the mean for the 12 months preceding the image acquisition date; due to inadequate variation across the two time periods, temperature was omitted from the final analysis. Where watersheds contained more than one CRU grid cell, the mean value was used.

Discharge data originated from a collection of records dating to the early 1950s, when an array of stream and precipitation gauges was installed in the Santa River basin. The historical dataset originally included daily time series for 17 stations, but after quality control analysis only nine stations were determined to be suitable for trend analysis (Baraer et al., 2012): Chancos, Colcas, La Balsa, La Recreta, Llanganuco, Los Cedros, Pachacoto, Parón, and Querococha. Of these 9 stations, 2 were eliminated for the present study because 1) Parón contains a glacial lake that is regulated by a drainage tunnel with flows intensively managed for hydroelectric power generation; and 2) the discharge record for Pachacoto was interrupted from 1992-1993 and in

1995. A geographic information system (ArcGIS 10.2) was used with a digital elevation model (ASTER GDEM v.2 from <http://gdem.ersdac.jspacesystems.or.jp/>) to generate watersheds based on the coordinates of the seven discharge stations. Four stream discharge variables were calculated from the data (Table 2). Mean annual discharge and dry season discharge should be markers of the influence of glacier retreat on the hydrology of medium to large watersheds in the study area. Mean annual discharge is for the calendar year coinciding with the image date. Dry season discharge is defined as the total discharge for the 2 months with the historically lowest precipitation (July and August) coinciding with the image acquisition year. Wet season discharge is the total discharge for the 2 months with the historically highest precipitation (February and March) preceding the image acquisition date. Ideally, lagged discharge variables could be created for preceding years to account for residence times. In this case, only a 6-year lagged discharge variable was created (discharge from 1981 and 1989) because the only preceding years in which the discharge data were gap free were 1981 and 1989. Note that the La Balsa site was omitted because of missing data in 1981 so $n = 6$ for this model only. The 6-year lagged variable was substituted into Model 3 and is referred to as Model 3A.

2.2.2. First Differencing Regression

For a panel dataset with observation i and two time periods ($t = 1$ or 2), the first differencing equation is expressed as:

$$y_{i2} = (\beta_0 + \delta_0) + \beta_1 x_{i2} + a_i + u_{i2} \quad (\text{time}=2) \quad (1)$$

$$y_{i1} = \beta_0 + \beta_1 x_{i1} + a_i + u_{i1} \quad (\text{time}=1) \quad (2)$$

where y_{it} is the response variable of interest, β_0 is the y intercept or constant, $\beta_0 + \delta_0$ is the change in the intercept from time 1 to time 2, β_1 is a coefficient of predictor variable x , x_{it}

represents predictor variables, a_i is the unobserved time constant factor (the unobserved effect), and u_{it} is the time-varying error (Wooldridge, 2009). After subtracting time 1 from time 2, the following equation results:

$$(y_{i2}-y_{i1})=\delta_0+\beta_1(x_{i2}-x_{i1})+(u_{i2}-u_{i1}) \quad (3)$$

or

$$\Delta y_i=\delta_0+\beta_1 \Delta x_i+\Delta u_i \quad (4)$$

where Δ represents the change from time 1 to time 2. The term ‘first differencing’ was coined because the unobserved effect, a_i , is ‘differenced away’ so that the time-constant unobserved effects are controlled for (Wooldridge, 2009, p. 458). The rationale is that time-constant variables are not likely to be factors driving change (Allison, 2009; Andreß et al., 2012); thus variables such as lithology and topography that are time-constant would not be included in the analysis. Statistical computations were conducted in STATA SE 12 using function xtreg and the fe option for fixed effects regression estimation. Robust standard errors are reported.

Assumptions for fixed effects regression were not violated, implying that model estimates are efficient and unbiased in regards to exogeneity, homoscedasticity, serial correlation, and measurement error (Andreß et al., 2012). Multicollinearity was detected among the following variables: mean annual discharge, dry season discharge, and wet season discharge. Similarly, multicollinearity existed among previous precipitation and dry and wet season precipitation; therefore, models were restricted to mean annual discharge and previous precipitation.

Model specifications were performed in two stages. First, bivariate regressions of change in wetland area on all the explanatory variables were computed. Second, regressions were completed following the hypotheses in Table 1 and Figure 1. The significance value selected was

0.1 (two-tailed). For fixed effect regressions, STATA produces three R^2 values: within, between, and overall. The within R^2 is the most commonly used for interpreting first differencing regressions (Allison, 2009, p. 19), reporting the explained portion of the within variance using the mean deviation variables (Allison, 2009; Andreß et al., 2012). All R^2 values reported herein are within R^2 s.

3. Results

Wetland change could be best predicted from changes in glacier area and mean annual discharge, although prior precipitation was also statistically significant (Tables 4, 5). First, the bivariate regressions were computed to test H1 and to determine whether or not any of the explanatory variables might individually explain change in wetland area. One variable, prior precipitation (PrePrior) was highly statistically significant ($p < 0.001$, two-tailed) and the within R^2 was 0.5571 (Table 4). Results of the multivariate regressions that correspond to the hypotheses described in Table 1 and Figure 1 are reported in Table 5. Of the seven hypotheses, only H3 passed the stated acceptance criteria of $p < 0.1$; consequently, hypotheses 1, 2 and 4 to 7 were rejected. Model 3 failed to be rejected and shows that change in glacier area and change in mean annual discharge were statistically significant at the 0.1 level (and borderline to 0.05 level), and within R^2 was 0.3431.

The first differencing regression used here indicated that change in glacier area and change in mean annual discharge were driving wetland change from 1987 to 1995. Results from Model 3 estimated that for every 1 ha decrease in glacier area, wetland area increased by 0.07 hectares, holding all other factors constant. For every $1 \text{ m}^3 \text{ s}^{-1}$ increase in annual discharge, wetland area increased by 72 ha, holding all other factors constant. Relative to change in glacier area, change in mean annual discharge accounted for the largest magnitude of wetland change

from 1987 to 1995. This is consistent with the constant coefficient in Model 3 that was not statistically significantly different from zero. In other words, if glacier area was not changing (an absence of recession) and if stream discharge was not changing, we would expect change in wetland area in the study area to be minimal. In addition, results from the bivariate regression of change in prior precipitation on change in wetland area shows that there is a possibility that increased precipitation could increase wetland area, a concept we consider in the discussion section.

Furthermore, we wanted to explore a longer lagged discharge variable in the event that the 12 month lagged discharge variable, Mean Annual Discharge (Table 2), did not capture the interaction. In other words, is the hydrologic residence time longer than the 12 months preceding the image acquisition date? To address this question, a 6-year lagged discharge variable was created as described in the methods section. The 6-year lagged variable was substituted into Model 3 and is referred to as Model 3A. The analysis revealed that the 6-year lagged discharge variable did not improve the estimations (Table 6). Six year mean annual discharge and change in glacier area were not statistically significant and the R^2 value declined to 0.0377. Therefore, we concluded that the hydrologic residence time is not 6 years. It is possible that the residence time is shorter or longer and could be statistically significant, but our hydrologic dataset did not permit testing of other residence times because of data incompleteness (see Section 2.2.1.).

Table 4. Bivariate regressions of change in wetland area on explanatory variables.
Robust standard errors are shown. * Does not include La Balsa watershed; n=6

	Constant	Robust SE	Coefficient	Robust SE	p Value	R² Within
Δ Glacier Area	712.4923	17.4413	0.0005	0.0022	0.799	0.0009
Δ Lake Area	728.9068	28.7390	-0.0351	0.0856	0.696	0.0035
Δ Mean Annual Q	684.5593	58.5739	2.1468	3.8604	0.598	0.0137
Δ 6 Yr Mean Annual Q*	223.8707	130.0444	-2.5637	30.0275	0.935	0.0035
Δ Dry season Q	719.7329	21.2511	-0.4332	3.5414	0.907	0.0004
Δ Wet season Q	696.8809	31.6755	0.7726	1.2085	0.546	0.0108
Δ PrePrior	-437.3186	157.0036	3.0874	0.4199	0.000	0.5571
Δ 6 Yr PrePrior	688.5121	61.4422	0.0398	0.0855	0.658	0.0421
Δ Pre July Aug	712.1690	5.3583	0.4042	0.4363	0.390	0.0278
Δ Pre Feb Mar	701.4043	42.1073	0.1105	0.2959	0.722	0.0280

Table 5. Model results for multiple regressions. Model numbers correspond with hypotheses described in Table 1. Robust standard errors are reported in parentheses below each coefficient.

		Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Constant	Coeff	712.4923	2327.0300	218.9284	1262.1010	-566.9294	-1279.7660	-504.7602
	S.E.	(17.4413)	(2397.4540)	(219.3361)	(2139.7250)	(411.7595)	(1823.6730)	(220.8903)
	p value	0.000	0.369	0.357	0.577	0.218	0.509	0.062
Δ Glacier Area	Coeff	0.0005	-0.0874	-0.0743	-0.1207	.01851	0.0582	
	S.E.	(0.0022)	(0.1303)	(0.0303)	(0.0694)	(0.0860)	(0.1006)	
	p value	0.799	0.527	0.050	0.133	0.837	0.584	
Δ Lake Area	Coeff		-2.7187		-1.6717		0.9693	
	S.E.		(4.0455)		(3.1715)		(2.5702)	
	p value		0.527		0.617		0.719	
Δ Mean Annual Q	Coeff			71.9332	64.5858	-22.1651	-30.8301	-3.8722
	S.E.			(30.4054)	(40.2777)	(86.5298)	(81.0252)	(2.9604)
	p value			0.056	0.160	0.806	0.717	0.239
Δ Pre Prior	Coeff					3.9381	4.4791	3.4249
	S.E.					(2.6804)	(2.6185)	(0.6652)
	p value					0.192	0.138	0.002
R^2 Within		0.0009	0.1334	0.3431	0.3896	0.6159	0.6264	0.6088

Table 6. Results for fixed difference regressions on Model 3 and 3A. Model 3A excluded La Balsa (n= 6) and substituted a 6-year lagged discharge variable for 12-month discharge variable. Model numbers correspond with hypotheses described in table 1. Robust standard errors are reported in parentheses below each coefficient.

		Model 3	Model 3A
Constant	Coeff	188.7638	175.0493
	S.E.	(143.7029)	(183.5832)
	p value	0.246	0.384
Δ Glacier Area	Coeff	-0.1229	0.0399
	S.E.	(0.0743)	(0.1068)
	p value	0.159	0.723
Δ Mean Annual Q	Coeff	88.5584	
	S.E.	(34.8529)	
	p value	0.052	
Δ Mean Annual Q 6	Coeff		-16.4203
	S.E.		(46.1591)
	p value		0.737
R^2 Within		0.4110	0.0377

4. Discussion

Connectivity between land change and hydrologic processes are not well understood in tropical mountain regions, but the methods and results presented here show that a spatially explicit econometric analysis demonstrates a promising approach that can be further developed and used by land change scientist and land managers preparing for change associated with glacier recession. We are aware of only one other study located in the tropics that investigated the connections between landscape and hydrology. Mosquera and others (2015) used linear regression to estimate the relationship between stream runoff and wetlands in the Ecuadorian *páramo*. They found that larger wetlands are associated with higher stream discharge. Our findings are consistent with Mosquera and others (2015) because we show that wetland area and discharge are linked; however, our innovation is the adoption of first differencing regression that

incorporates a temporal variable. Adding in the element of temporal change and attempting to elucidate causality is crucial for research in highland landscapes because they are experiencing spatial transformation that will impact ecosystem services. Sociologists have used first differencing regression to evaluate environmental change as it relates to shifts in populations, economic forces, and other factors (Jorgenson and Clark, 2011; Clement and Podowski, 2013; Clement et al., 2014), but we are not aware of any other applied study that uses spatially explicit biophysical variables to examine connectivity between hydrology and landscape change.

The indications that changing glacier area and changes in mean annual discharge were associated with change in wetland area could be evaluated within the context of the peak water concept. Using the same discharge data used here, Baraer et al. (2012) found the watersheds were already past peak water and discharge had begun its decline by the 1980s. All seven watersheds evaluated were experiencing decreasing discharge and higher variability. Wetland area decreased from 2000-2011 in one valley in the Cordillera Blanca as reported in Bury et al. (2013); findings by Polk (2016) show wetland area increased from 1987 to 1999, then decreased in area from 1999 to 2010. These two observations suggest that wetlands follow the peak water curve, but with a possible time lag as illustrated in Figure 3. Projected further decreases in hydrological input into wetlands in the future can be expected to result in their degradation and soil desiccation. The effects of reduced hydrological input should be observable on the spatial distribution and configuration of wetland patches. Spatial effects may include wetland fragmentation, attrition, dissection, shrinkage, and perforation. These patch modifications would likely result in associated ecological effects including loss of species adapted to or dependent on saturated substrates (Lee et al., 2015; Quenta et al., 2016). Ecosystem services provided by the wetlands, such as carbon and water storage, nutrient filtration, and biomass production would

decrease (Charman, 2002; Dise, 2009) while atmospheric radiative forcing would potentially increase (Petrescu et al., 2015). Figure 3 shows the contemporaneous effects of changing wetland area on ecosystem services. Changes in wetland geomorphic processes and vegetation composition could also occur as spatial changes take place and represent an opportunity for future research.

The estimates reported here hold true for 1987 to 1995 in our study area, but would likely differ if a nonlinear relationship between mean annual discharge and change in wetland area is generally expected over a longer period that would exceed satellite and hydrologic observation records. In deglaciating watersheds, research (Barnett, Adam, & Lettenmaier, 2005; Mark & Seltzer, 2003; Milner, Brown, & Hannah, 2009) predicted that precipitation will increasingly control watershed hydrology because the effect of glacier meltwater will diminish. The statistically significant relationships between changes in wetland area and prior 12-month precipitation (PrePrior) supports these previous predictions and suggests that ecosystems may already be responding to losses in ice cover (p-value = 0.000, within R^2 is 0.5571, Table 4). Wetlands in the study area are a complex of bogs, fens, and minerogenous meadows and based on our results, the wetlands remaining in some watersheds may be transitioning to an increased dominance of precipitation-dependent bogs. With the implementation of a continuous hydrologic monitoring network, future research could take into account the influences of other wetland water sources such as groundwater and surface water flows. Over decadal time scales, glacier recession will likely trigger changes in vegetation cover (Young et al., 2017) and soils; future research should evaluate the linkages and feedback mechanisms between changes in vegetation, soils, and hydrology in tropical mountain landscapes.

Figure 3. The proposed relationships among peak water, glacier recession, changing glacier discharge, wetland area, and wetland ecosystem services with the approximate period of this study indicated by the grey shaded area.

5. Conclusion

Decadal evaluations of other similar high mountain ecosystems show that wetland area may increase (H. Li, Xu, & Zhao, 2014; Postigo et al., 2008), decrease (Bury et al., 2013; Z. W. Li et al., 2015; Nie & Li, 2011), exhibit stasis (Gao, Li, & Brierley, 2012), or both increase and decrease (Yao, Zhao, Gao, Sun, & Li, 2011). More could be done to evaluate effects of hydrologic connectivity (DeFries and Eshelman 2004, Wohl et al.2012), especially in light of the possible nonlinear relationships implied by a peak water hydrograph expected during glacier retreat (Figure 3). The first differencing regression approach used in this study provides an analytical framework useful in situations where climate change or altered hydrological regimes may drive land cover transformations. Integrating additional econometric methods into land change science will facilitate further interactions among researchers interested in socio-ecological and socio-hydrological systems that may be vulnerable to climate change (Carey et al., 2014; Chapin, Kofinas, & Folke, 2009). Unexpected interactions can be revealed and here

showed that wetlands change with glacier retreat and stream discharge dynamics, but the influence of these variables may diminish as future glacier cover decreases and precipitation becomes the main driving force of wetland spatial change.

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Graphical Abstract. This research proposes relationships among peak water, glacier recession, changing glacier discharge, wetland area, and wetland ecosystem services with the approximate period of this study indicated by the grey shaded area.