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Case Study: Reconstructing the 2015 Dulcepamba River Flood Disaster

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Key Terms: ***Model, Hydraulic, Hydrologic, Flood, Hydropower***

ABSTRACT

In March 2015, the village of San Pablo de Amalí on the Dulcepamba River in Ecuador was hit by a flood that killed three residents, destroyed five homes, and eroded several hectares of farmland. Residents asserted that the recent construction of a run-of-the-river hydroelectric facility built in the river channel directed flood flows toward the village, causing the associated damage and fatalities. We conducted a forensic hydrologic and hydraulic analysis of the catchment to assess potential causal mechanisms affecting flooding, including the construction of the hydroelectric facility. Hydrologic analysis demonstrated that the river flows produced by the March 2015 storm were equivalent to a 6-year return interval event, with a discharge of 58.6 cms, not the much more extreme 33-year return interval, 400-cms event that had been suggested in a report produced by the hydroelectric company. Hydraulic modeling determined an ∼2-m elevation surcharge of water attributable to the hydroelectric facility, suggesting that damage to the village would not have occurred without the obstruction created by debris blockage of the hydroelectric plant intake. Hydrologic modeling also quantified monthly totals of water availability in the Dulcepamba watershed, including average dry-season flow volumes. When compared to flow volumes allocated to the hydroelectric operator, the modeling indicated that the seasonal water availability in the Dulcepamba watershed is not sufficient to collectively meet the minimum in-stream environmental flow requirements, the agriculture demands from local subsistence irrigators, and the flow volumes allocated to the hydroelectric operator.

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INTRODUCTION

The Dulcepamba watershed is located in central Ecuador in Bolívar Province. The catchment covers nearly 500 km^2 and extends from the ∼3,200-m-elevation highlands of the Andean plateau down to the coastal foothills at ∼100 m above sea level. The northern and eastern areas of the watershed are particularly rugged and largely forested or covered with shrub brush. Land uses in the gentler sloping downstream portions of the watershed are dominated by agriculture, including a variety of crops. The agrarian town of San Pablo de Amalí is located along the left bank of the Dulcepamba River at ∼420 m elevation. The location is shown in Figure 1.

In 2012, Hidrotambo, S.A., began construction of a water intake facility for a low-head, run-of-the-river hydroelectric plant without pondage in the channel of the Dulcepamba River. The intake of the hydroelectric structure was located in the original riverbed adjacent to San Pablo de Amalí, and flow not passing through the facility was directed in a channel toward the town. In addition, as part of the operating license for the hydroelectric facility, Hidrotambo had obtained a right to seasonal diversions from the Dulcepamba River in the following volumes: up to 6.50 cubic meters per second (cms) from December 15 to June 14 and up to 1.96 cms from June 15 to December 14.

A storm and resulting flood on March 19–20, 2015, sent water into the town of San Pablo de Amalí, causing severe bank erosion and undermining of the town, which caused several deaths, loss of property, and damage to the only road access to the town. Eyewitness accounts and photographic evidence indicate that the flood mobilized large volumes of coarse sediment and other debris along the Dulcepamba channel and floodplain. Witness reports and photographs (Figure 2) taken after the flood suggested complete or near-complete blockage of the hydroelectric intake and

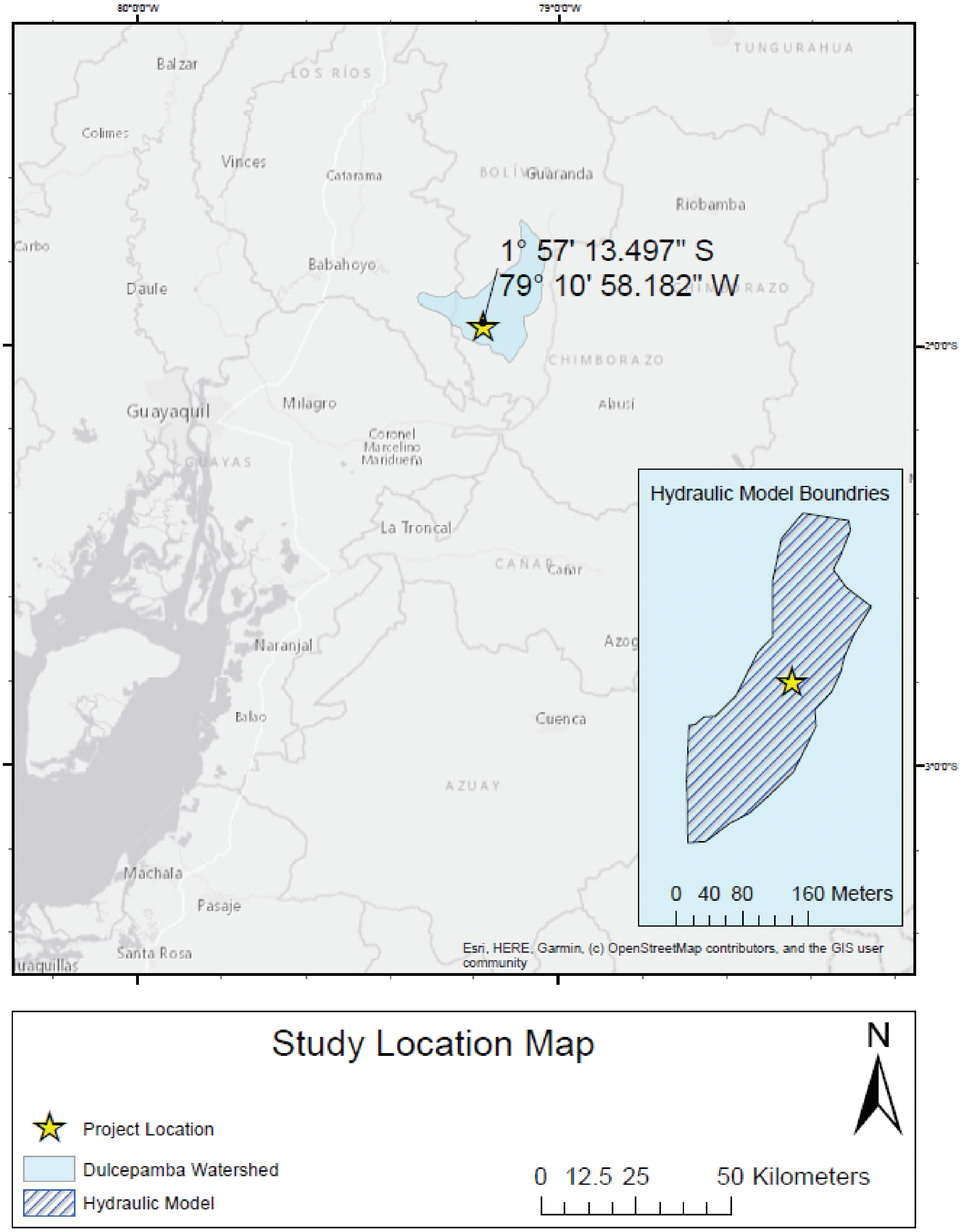

Figure 1. Study location map, San Pablo de Amalí identified by the yellow star. Map inset shows the boundaries of the hydraulic model.

Figure 2. Debris blocking the intake structure in the original river channel.

adjacent channel by coarse sediment, woody material, and other debris.

A report produced by the power plant owner, Hidrotambo S.A. (Soria, 2015), suggested that the March 2015 flood had a peak flow of 400 cms and a return interval of 33 years. According to Soria (2015), flood flows through San Pablo de Amalí began on March 20 and lasted 4 days. In contrast, eyewitness accounts and the available precipitation and discharge measurements indicate that the flood wave began to pass through San Pablo de Amalí on March 19, with peak flows lasting only 1 to 2 days. Soria (2015) ascribed the 2015 flood damages in San Pablo de Amalí to extreme precipitation in the watershed.

METHODS

Hydrologic and hydraulic models were developed to simulate conditions in the Dulcepamba watershed and in the Dulcepamba River through San Pablo de Amalí. Precipitation and stream flow data were obtained from local sources and from the Instituto Nacional de Meteorología e Hidrología (INAMHI) in Ecuador. Input data, simulation durations, and sources for both the hydrologic and the hydraulic models are described in the sections below. Available data were used to simulate historical hydrologic conditions in the basin as well as hydrologic and hydraulic conditions during select storm events, including the March 2015 flood.

Hydrologic Model

A hydrologic model was developed for the historical record in the Dulcepamba River basin. The Hydrologic Modeling System software, HEC-HMS (Hydrologic Engineering Center [HEC], 2016d), was used to analyze the period of record (through continuous simulation), several historic flood events, and the March 2015 flood. Model results were generated for three purposes: (1) to determine the recurrence interval of the 2015 flood and other high-water events; (2) as input to the hydraulic model of the Dulcepamba River to create a more detailed analysis of the hydraulic and geomorphic processes that occurred prior to, during, and after the March 2015 event; and (3) to assess water availability for Dulcepamba basin water rights.

Basin Data and Model Parameters

Shapefiles of the watershed boundaries, precipitation isohyets, stream paths, land use, soil type, and vegetative cover were used to delineate sub-basins within the watershed and to estimate initial hydrologic infiltration, storage, and loss parameters (Gobierno Autonomo Decentralizado Municipal Chillanes [GADMC], 2012a, 2012b). Considering differences in land use, vegetation, and slope, the Dulcepamba model was split into three sub-basins: Upper, Middle, and Lower, shown in Figure 3. Cross sections were obtained for the following reaches of the river channel and floodplain, including San Pablo de Amalí, Amalí-Salunguiri, Chima Guapo, Chima Pesqueria, Congon Tendal, Limon, and Sicoto. The cross-section data were used in the hydrologic model as input geometry for hydraulic routing. Within the model, the Simple Canopy, Simple Surface, Deficit and Constant Loss, Clark Unit Hydrograph, Recession Baseflow, and Monthly Evapotranspiration methods were used to represent hydrologic processes in the basin.

Annual precipitation in the study area averages around 1,450 mm per year but can range up to 2,000 mm per year in the higher elevations of the watershed (GADMC, 2012a). Most of the annual precipitation occurs from December to April, as shown in the average monthly rainfall histogram in Figure 4 (monthly data from the Chillanes precipitation gage). Precipitation in the basin ultimately accumulates in the Dulcepamba River, which flows southwesterly toward the coastal plains. Rainfall data were available for several locations within and near the watershed. Precipitation gages used in the study are listed in Table 1 and shown in Figure 3. Data for Chillanes (Code# M0130), San Pablo de Atenas (Code# M0131), and

Table 1. *Precipitation gages used in the Dulcepamba HMS model.*

Gage Name	Latitude	Longitude	Frequency
Chillanes	−1.981	−79.068	Daily
San Pablo de Atenas	−1.822	−79.069	Daily
Sanabanan	−1.974	−79.102	Daily
San Pablo de Amalí	−1.951	−79.167	5 min
San Vicente	−1.919	−79.138	Daily
San Jose Del Tambo	−1.943	−79.236	Daily

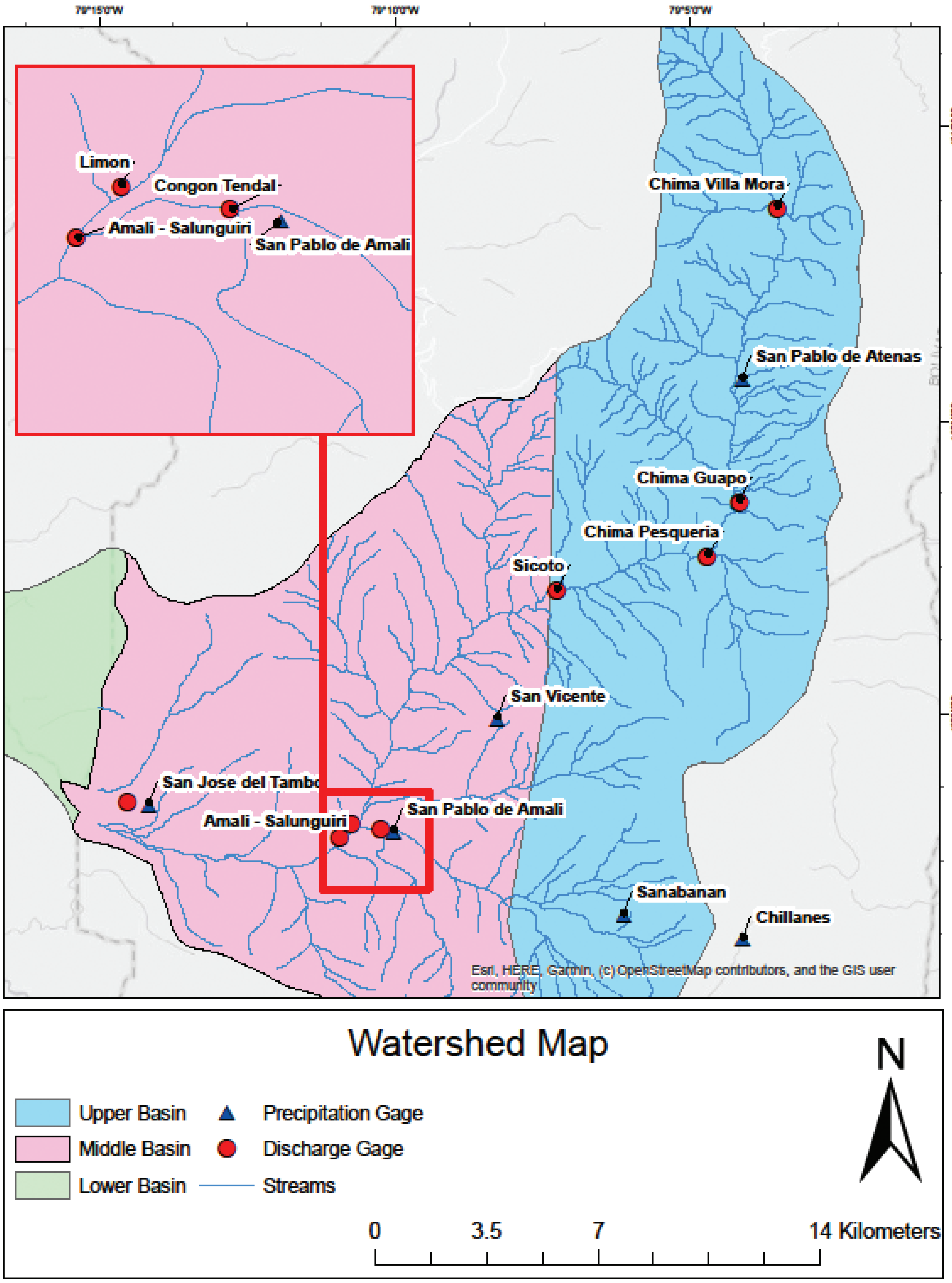

Figure 3. Locations of precipitation and discharge gages in the Dulcepamba watershed; precipitation data.

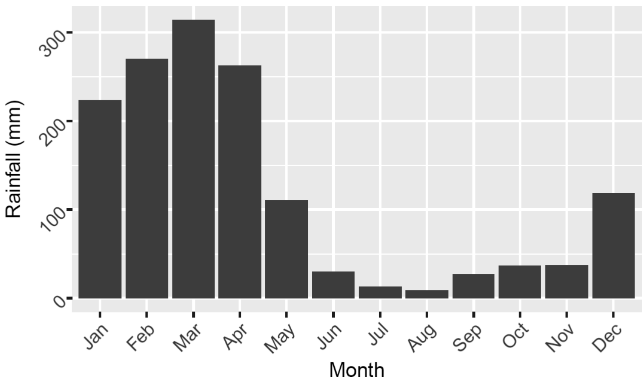

Figure 4. Monthly average precipitation histogram for the Chillanes precipitation gage; discharge data.

San Jose Del Tambo (Code# M0384) were available from INAMHI. Data from Chillanes and San Pablo de Atenas were particularly useful for the historical study, as records go back to January 1, 1963, and August 1, 1968, respectively. Data for the remaining sites were recorded and provided by a local nongovernmental organization (Instituto de Estudios Ecologistas del Tercer Mundo [IEETM]). The sites maintained by IEETM also recorded evapotranspiration data, which were useful for verification of evapotranspiration in the model and as input for the more recent historical simulation events. Given the available gages and data, the inverse distance method was most appropriate.

Homogeneous and continuous historical river discharge data were available for only one gage site in the basin at Sicoto. The gage site (Code# H0334) and associated data are maintained by INAMHI. Daily average flow rates (cms) were available beginning January 1, 1968. Although several days are missing from the record, sufficient data existed for calibration of the hydrologic model and frequency analysis. The Sicoto gage site is located nearly 12 km upstream of and about 1,500 m higher in elevation than San Pablo de Amalí. Daily flow data were also available for a gage site downstream of San Pablo de Amalí at San Jose del Tambo, also maintained by INAMHI (Code# H0395). Although measurements are available only from 1968 to 1973, these data were still useful for calibrating the historical period of record as well as providing an expectation of typical flow magnitudes downstream of San Pablo de Amalí. Both INAMHI gage locations are shown in Figure 3.

Instantaneous discharges were measured at several additional sites within the watershed, located primarily at Chima Guapo, Chima Pesqueria, Chima Villa Mora, Congon Tendal, Amalí-Salnuguiri, and San Pablo de Amalí (locations shown in Figure 3; data measured and provided by IEETM). For most of the period of study, these were intermittent, instantaneous measurements, with significant and variable time periods between measurements. These data provided helpful snapshots, but they were not used for calibration. Two exceptions were measurements from the Congon Tendal tributary and for San Pablo de Amalí. Data of representative dry-season flows and storm events were available for Congon Tendal. More consistent flow discharge measurements were available for San Pablo de Amalí from March 2014 to February 2017.

Hydraulic Model

A two-dimensional (2D) hydraulic model was developed using the River Analysis System software developed by the U.S. Army Corps of Engineers, HEC-RAS 5.0.3, to inform hydraulic conditions and geomorphic processes near San Pablo de Amalí during the March 2015 flood (HEC, 2016a, 2016b, 2016c). The model used the output from the hydrologic model and hydrologic and topographic measurements from the study reach. The hydraulic model simulations were then used to determine flow depths, velocities, and shear stresses for the March 2015 flood. To assess the impact of the hydroelectric facility, the hydraulic simulation of the 2015 event was run as if the full flow volume were passed through the reach in the absence of blockage, and these water surface profiles were compared with measured elevations during the 2015 flood.

The terrain model was developed from topographic survey data of the study reach channel and floodplain (measured by Facultad de Ingeniería, Pontificia Universidad Católica del Ecuador, and provided by IEETM). A comparison of the river location for pre- and post-construction as well as post-flood conditions is presented in Figure 5. The model computational grid spacing was typically 5 m and reduced to as little as 1 m in areas with the steepest slopes. Hydrologic data for the upstream boundary of the hydraulic model were entered for model calibration, flood simulation, and flood capacity testing. The computational time step was 0.5 seconds, and roughness (Manning's n) was initially set to a uniform value of 0.1 based on recommended values for modeling flows on a steep slope (Jarrett, 1984).

For model calibration, four measured flow rates were used. Manning's n calibration focused on average velocity and depth at channel cross sections. Establishing matching cross-section profiles between the measured data and modeled results was not possible due the several discrepancies in spatial data, including that (1) the topographic survey did not include bathymetric measurements for the riverbed, (2) the cross-section measurements provided by the Dulcepamba Project Team indicated that the profile changes over

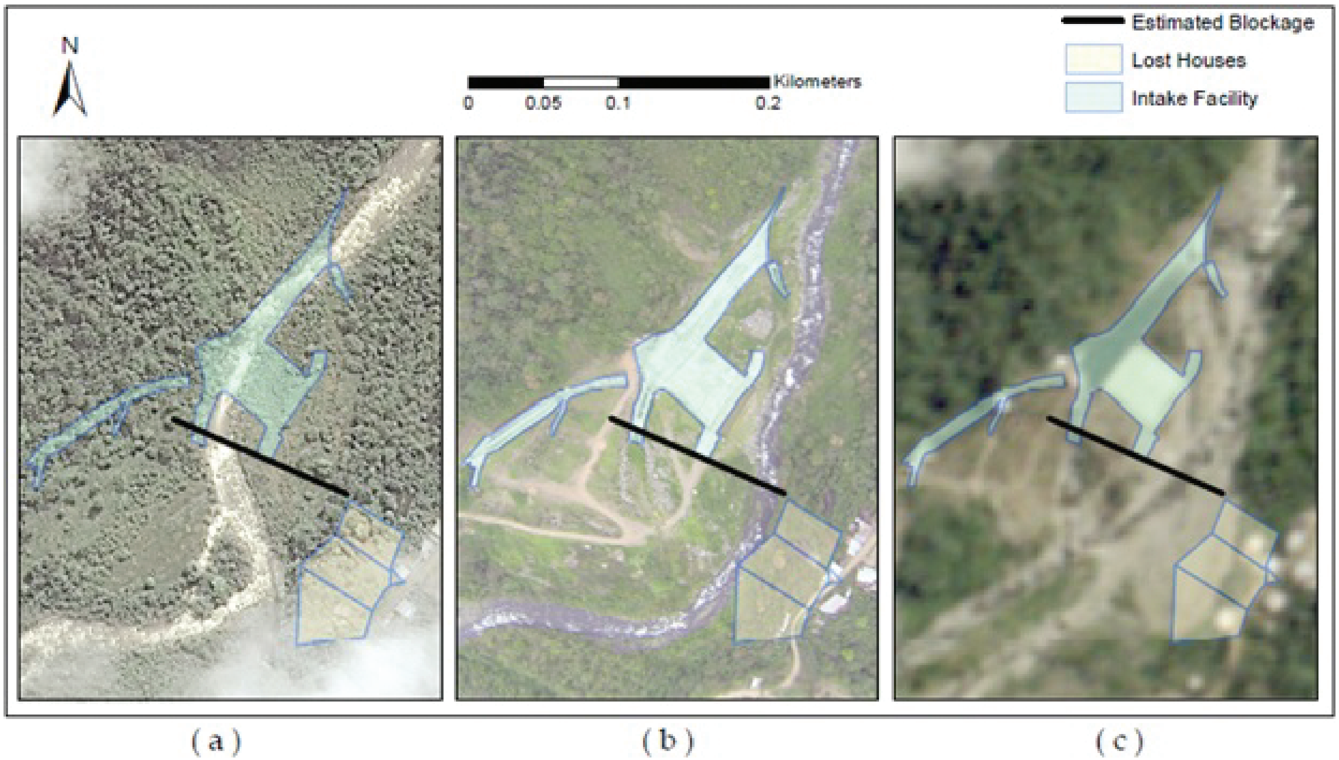

Figure 5. San Pablo de Amalí on the Dulcepamba River showing riverbed, hydroelectric power plant, and areas of housing damage (a) before construction, (b) after construction, and (c) after the flood event of March 2015.

time, and (3) the location of the velocity and depth measurements was acquired by IEETM using a GPS unit of unknown precision. For this reason, calibration was deemed sufficient for the purpose of this study when all four calibration flows produced depth and velocity results in the range of observed measurements at the approximate location they were taken. Additionally, since the reach is relatively small, it was assumed that secondary inflow and outflow would be negligible to the magnitude of the flood event, and therefore flow rates at both boundaries should be consistent with each other. The mean velocity and depths in the reach for each of the calibration flows are presented in Table 2. As a final verification of the capacity of the natural system, simulations were run using synthetic flows, incrementing inflow rates from 20 to 500 cms over a 7-hour time period.

RESULTS

Hydrologic Model

The HEC-HMS model was calibrated to historical rainfall-runoff events and to the period-of-record data. Model parameters were adjusted (within known acceptable limits) until the model best reproduced the observed discharges at the available gage locations. Two groups of calibration studies were completed: a period-of-record study and individual events.

Table 2. *Measured and modeled flows, depths, and velocities used for pre-flood condition calibration.*

	Measured			Calculated Mean	
Date	Flow Rate (cms)	Depth (m)	Velocity (m/s)	Depth (m)	Velocity (m/s)
January 7, 2014	8.39	0.45	0.67	0.66	0.93
January 31, 2014	38.89	1.18	1.15	1.55	1.75
March 25, 2014	12.38	0.66	0.79	0.82	1.11
October 16, 2014	2.77	0.53	0.32	0.34	0.55

Table 3. *Final HMS model parameters.*

Parameter	Sub-Basin Upper	Middle	Lower
Area (km^2)	221.5	204.1	48.2
Maximum canopy storage (mm)	3	3	—
Maximum surface storage (mm)	3	4	—
Maximum deficit (mm)	18	20	18
Constant loss rate (mm/hr)	3.3	2.6	2.7
% impervious	4	6	6
Time of concentration (hr)	5	7	6
Storage coefficient (hr)	22	25	15
Baseflow recession constant	0.95	0.95	—
Baseflow ratio	0.5	0.45	—

A continuous period-of-record simulation was completed with two objectives. The first was to determine baseline model values that most accurately reproduced observed flow data at the Sicoto and San Jose del Tambo flow measurement sites. A summary of the finalized model parameter values is given in Table 3. The second objective was to perform a flood-frequency analysis at San Pablo de Amalí through development of a historical hydrograph. Accordingly, a simulation was completed for the period of record from January 1, 1969, to December 31, 2016. Results were produced at a daily time step to compare with the available historical data.

Several historical events were modeled to further refine the calibration parameters and assess model accuracy. Simulations were completed for runoff events in April 1970, March 1989, January 1993, February 2008, and February 2017. These events were chosen to demonstrate model response to a range of hydrologic and meteorological conditions. Model parameters related to base-flow levels and soil moisture conditions were slightly adjusted to account for antecedent basin conditions for each simulation. All simulations were run at a daily time step to provide an appropriate comparison to the available observed flow data. Error in peak flows and flow volumes at Sicoto and San Jose del Tambo between modeled and observed flow values for each calibration event is given in Table 4. The model simulated the peak flows with high accuracy. In some cases, the timing of peak flow did not match; these mismatches are attributable largely to errors associated with the daily resolution of the data. The modeled flow volume for each event was also in acceptable agreement with observed values, except for the January 1993 event (a drought-year event). Although the 1993 percent error was high relative to the other simulations, the overall volume of error was still low. Results of the calibration events demonstrate that the model accurately simulated both high- and low-flow events.

Subsequent to calibration, the model was run for the period March 1–31, 2015, which includes the March 2015 flood event. Model results were again produced at a daily time step to provide appropriate comparison to the daily gage data at Sicoto. The full month was modeled to assess the following: antecedent conditions in the basin, response to pre-storm conditions, response to the peak event, and flow recession after the storm. The model produced highly accurate results of the event for the Sicoto gage location, as shown in Figure 6. Peak flow error was only 1.56%, total flow volume error was 0.86%, and the model accurately simulated the timing of the peak flow and flow recession.

A hydrograph of the March 2015 event was also produced for the river at San Pablo de Amalí; however, gage data were not available during this event. Modeled peak flow during the March 2015 event was 58.6 cms (shown in Figure 7).

After completing calibration based on the historical record, the maximum daily flow for each year of the analysis (1969–2016) was calculated. A flood frequency analysis was then completed on the peak flows using a log-Pearson type III distribution shown in Table 5. For the March 2015 event, the frequency analysis indicates a return interval of approximately 6 years for the flow at San Pablo de Amalí, confirming eyewitness and other local reports that the March 2015 event was not an extraordinary storm.

Table 4. *Calibration event error analysis of hydrologic model.*

Location and Event	Discharge Computed Peak (cms)	Observed Peak (cms)	Percent Error	Computed Volume (1,000 m^3)	Observed Volume (1,000 m^3)	Percent Error
Sicoto						
April 1970	7.8	7.4	5.41	13,195	13,501	2.27
March 1989	13.3	12.5	6.40	23,532	23,827	1.24
January 1993	3.2	3.0	6.67	1,870	1,559	19.95
February 2008	27.8	25.8	7.75	23,445	25,807	9.15
March 2015	19.5	19.2	1.56	14,217	14,340	0.86
San Jose del Tambo						
April 1970	32.7	31.7	3.15	61,933	63,420	2.34

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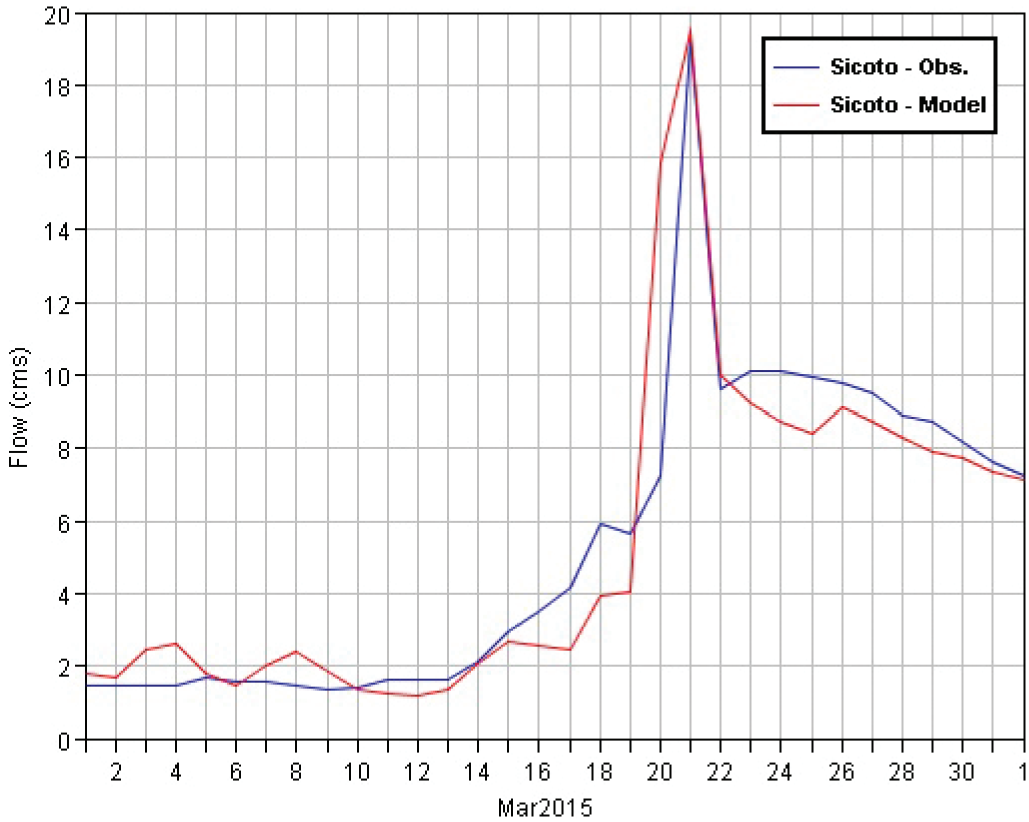

Figure 6. Modeled and observed flows at Sicoto for the March 2015 flood event.

The Dulcepamba hydrologic model was also used to estimate monthly flow volumes and daily flows available for water diversion. Cyclical analysis was completed for the modeled discharge at San Pablo de Amalí to determine the average, 90%, and 10% exceedance levels for daily and monthly flows over the period 1969–2016 (shown in Table 6). Similar analysis could be extended to other locations in the Dulcepamba watershed.

Hydraulic Model

Hydraulic model simulations were run using flows for the March 2015 flood from the hydrologic analyses in this study. As-built plans were not available for the Hidrotambo intake facility. A conservative approach for the 2015 hydraulic simulation was run as if the full flow volume was passed through the reach without blockage. The result of this modeling was a water surface elevation approximately 2 m lower than the water surface elevation measured during the 2015 flood. The 2-m difference demonstrates the approximate hydraulic impact of blockage in and near the Hidrotambo intake facility. Modeling also provided a 2D distribution of velocities that were used to calculate the size of boulder where motion would occur (Julien 2002). Flow velocities and depths demonstrate that the peak flow of the March 2015 event could mobilize submerged boulders up to 1 m in diameter.

Table 5. *Sicoto and San Pablo de Amalí flow return intervals.*

	Percent Chance Exceedance Event (flow cms)						
Location	50% (2-yr)	20% (5-yr)	10% (10-yr)	4% (25-yr)	2% (50-yr)	1% (100-yr)	0.5% (200-yr)
Sicoto[a]	9.63	14.93	18.06	21.56	23.84	25.87	27.69
Amali[b]	26.19	48.91	71.16	110.50	150.10	200.62	264.48

[a]Observed data.
[b]Modeled data.

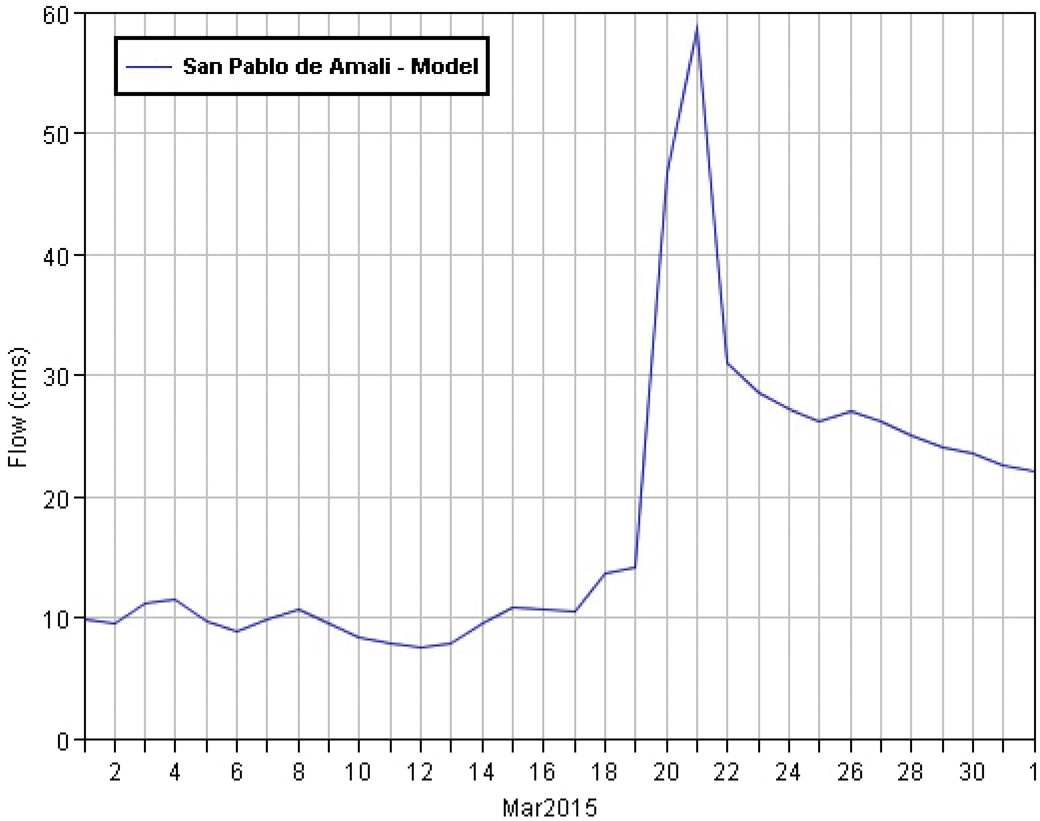

Figure 7. Modeled flow at San Pablo de Amalí for the March 2015 flood event.

DISCUSSION AND CONCLUSIONS

Hydrologic modeling of the Dulcepamba watershed accurately simulated observed hydrologic conditions and flood events. Results of the period-of-record simulation and simulations of specific flood events demonstrate that the March 2015 flood event was not an extreme flood, nor was it even a particularly rare event, confirming eyewitness accounts (R. Conrad, pers. comm., 2015, 2017). The model results and statistical flood analysis contradict the values suggested by the Hidrotambo report (Soria, 2015). The modeled peak flow in March 2015 was 58.6 cms (compared to the Hidrotambo report of 400 cms), and the peak flow lasted only 1 day (compared to the 4 days suggested by the Hidrotambo report). Furthermore, Soria (2015) indicated a return interval of 33 years for the 2015 flood event, while the hydrologic model demonstrates a return interval of just 6 years. The hydrologic model ultimately demonstrated that flooding and damage in San Pablo de Amalí cannot be ascribed simply to rare and extreme meteorological or hydrologic conditions in the watershed.

Additionally, the modeled flows at San Pablo de Amalí over the period of January 2010–February 2017 were compared to the hydroelectric facility seasonal water allocations (up to 6.50 cms for December 15–June 14 and up to 1.96 cms for June 15–December 14) and the minimum in-stream environmental flow requirement, 1.059 cms, which is set in statute by the

Table 6. *Average, 10%, and 90% exceedance flows at San Pablo de Amalí.*

	Monthly Flow Averages at Amalí (cms)											
	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Monthly average	7.51	10.6	12.13	12.85	8.69	4.91	3.21	2.71	2.82	3.08	3.42	4.42
90% monthly Average exceedance flow	4.39	5.12	5.11	5.85	4.6	2.99	2.43	2.31	2.27	2.42	2.43	2.58
10% monthly Average exceedance flow	10.14	20.2	19.95	21.33	12.81	8.09	4.45	3.21	3.57	3.87	4.24	5.48

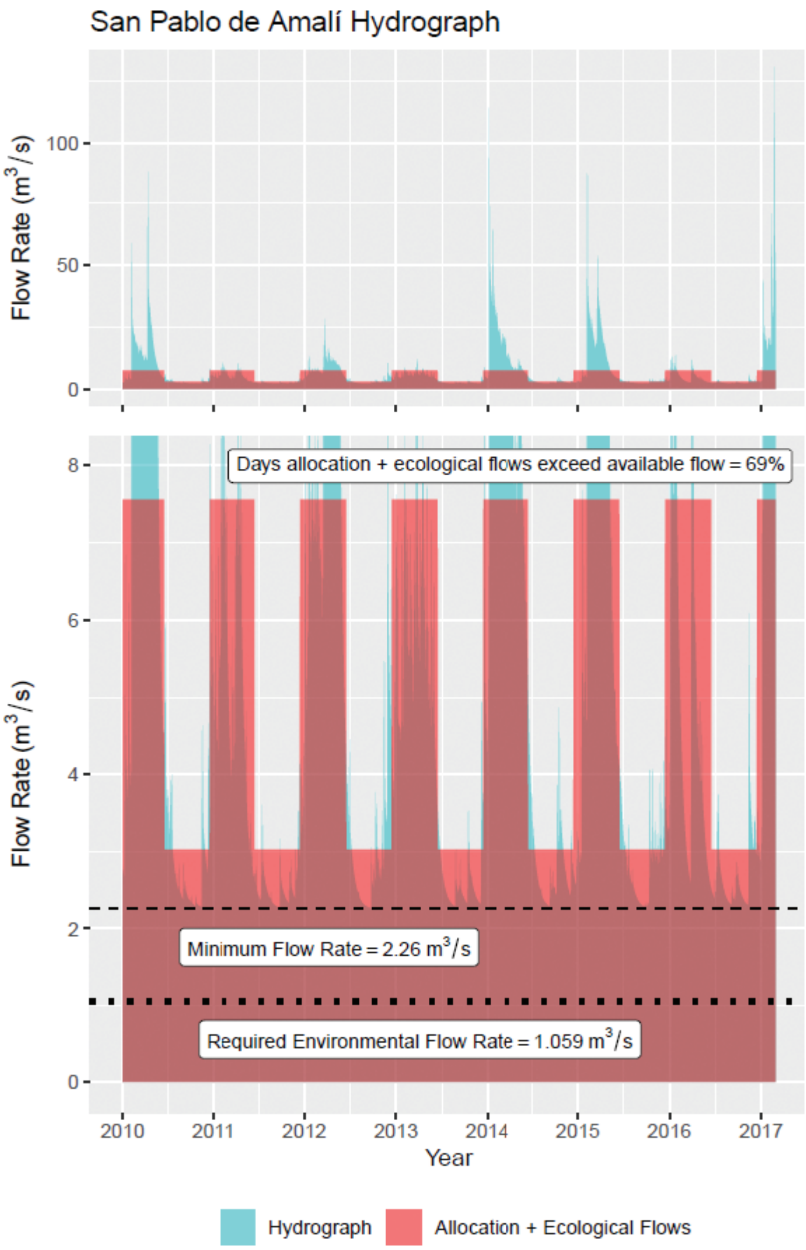

Figure 8. Comparison of available and allocated flow rates.

Ecuadorian government. The 8-year period was chosen to demonstrate water availability given current land use and hydrologic conditions in the context of the environmental flow requirement and the hydroelectric facility water rights. Model results indicate that the daily average flow at San Pablo de Amalí is below the sum of the environmental flow requirement and the Hidrotambo water allocation in 69% of days during the 2010–2017 period. These results suggest that the hydroelectric water rights would allow the facility to claim all of the flow in the river during part of the year, leaving little or no flow available for downstream irrigators, particularly during the dry summer season, when irrigation demands are highest. A comparison of available and allocated flow rates is shown in Figure 8. Despite recognition of this shortfall, Hidrotambo reportedly received an updated Dulcepamba water allocation in September of 2017 of 6.50 cms year-round (R. Conrad, pers. comm., 2019).

Hydraulic modeling of the Dulcepamba River near San Pablo de Amalí was successfully calibrated to available measurements. Because spatial and flow data were not available for the intake facility, the modeling here assumed that the full flow volume was passed

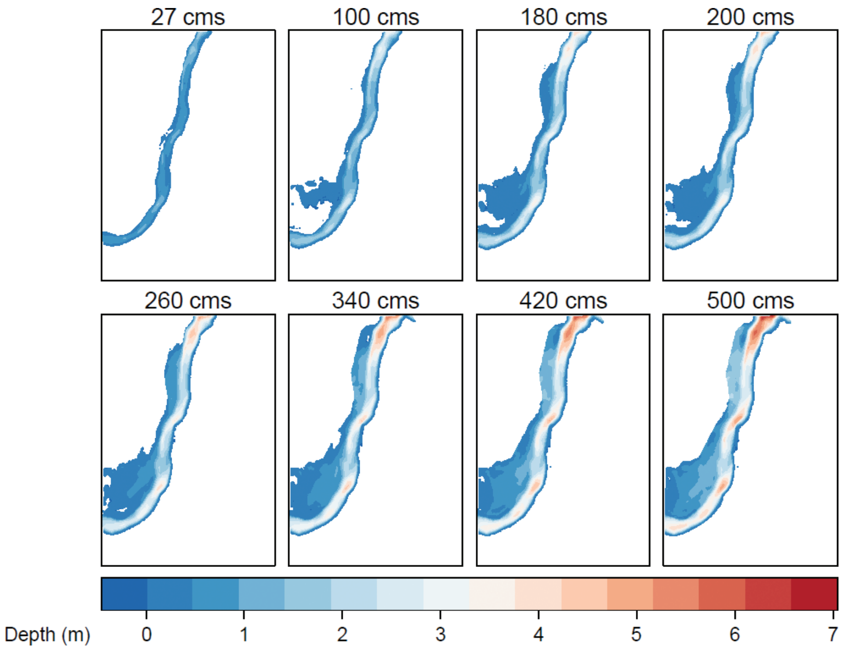

Figure 9. Flow capacity test with pre-flood geometry and depth for flow rates up to 500 cms. Model domain shown in Figure 1.

through the reach in the absence of the Hidrotambo hydroelectric construction. There was initial concern due to the 1:8 slope of the modeled reach, which is greater than the maximum slope of 1:10 recommended by the HEC-RAS. However, we determined through testing that (1) using relatively small cells in the steepest areas and (2) utilizing relatively high values of Manning's n, as suggested by Jarret (1984), the model would provide good approximations. For verification of these two assumptions, an additional study was performed in which a flow 3D model was produced for comparison. The comparison demonstrated that the HEC-RAS 2D model performed robustly when compared to the flow 3D model (Newmiller, 2017).

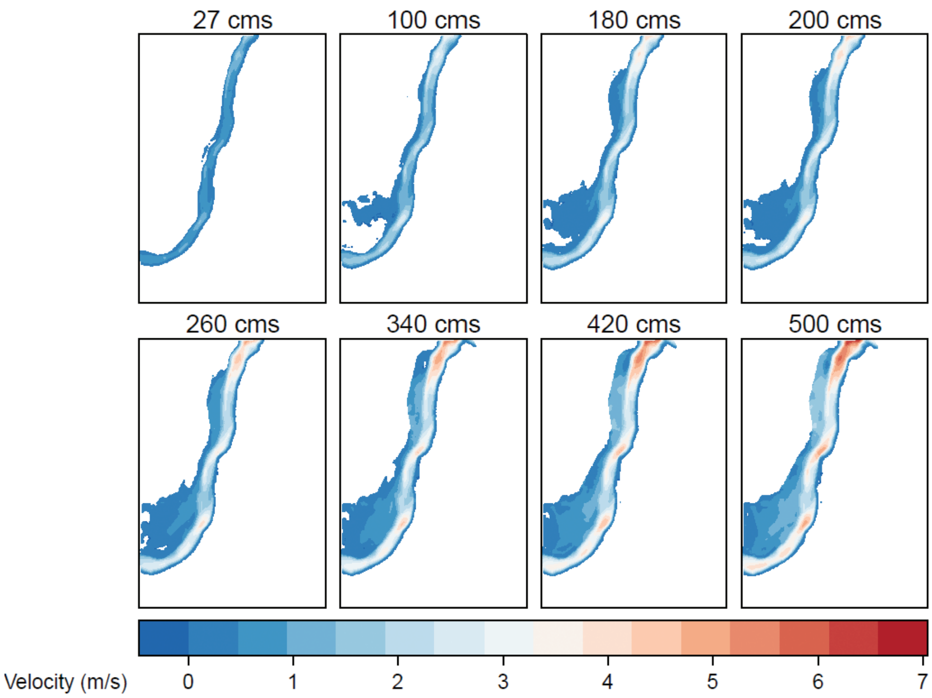

Figure 10. Flow capacity test with pre-flood geometry and velocity distributions for flow rates up to 500 cms. Model domain shown in Figure 1.

In the report released by Hidrotambo (Soria, 2015), the March 2015 flood peak was estimated at 400 cms. This value is significantly higher than the 58.6 cms calculated by the hydrologic modeling described above. In order to assess the 400-cms flow suggested in the above report, a synthetic hydrograph with flows increasing to 500 cms was simulated with the hydraulic model. The depth of flow results of this modeling are shown in Figure 9, and the flow velocity is shown in Figure 10. The 2015 flood, as calculated by the hydrologic model and as reported by Soria, was modeled through the modified channel without the added capacity of the intake facility. Even for the extreme flow rate reported by Soria (2015), an unobstructed flow would not have inundated the village of San Pablo de Amalí without additional obstruction of the channel at the hydroelectric intake. During the March 2015 flood, no significant obstruction was observed at any other location along the Dulcepamba River as occurred at the power plant intake. The obstruction directed the bulk of the flow toward San Pablo de Amalí and caused the 2-m increase in water elevations.

ACKNOWLEDGMENTS

Funding for the project was provided by the Center for Watershed Sciences at the University of California, Davis, as part of its international outreach efforts.

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