TITLE: Agua Salud Project Experimental Catchments Hydrometric Data, Panama

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ABSTRACT

The Smithsonian Tropical Research Institute (STRI) instrumented the Agua Salud (AS) Experimental Catchments as part of an ongoing series of land-cover related experiments in the steep, saprolitic, lowland, seasonal tropics of central Panama. The sites include tree plantations, rotational grazed pastures, native forests from 10 to over 80 years old, and a monoculture grassland. This data note provides a brief description of the instrumented catchments, rainfall and discharge data collection methods, data processing, and online availability.

1.0 Data Set Name

Agua Salud Hydrometric Data

2.0 Site Description and Research Findings

The research catchments are located in central Panama between latitudes 9.05° and 9.25°. Panama has a humid tropical climate and exhibits a significant rainfall gradient with annual precipitation varying from 1650 mm on the southern Pacific side to 2970 mm on the northern Atlantic side. Soils in the region have high clay content with thick layers of saprolite underlain by deeply weathered bedrock. The underlying bedrock is a mixture of Cretaceous to Upper Tertiary age volcanic and intrusive rocks (Harmon, 2005). Preferential flow is common in these catchments which results in infiltration rates and hydraulic conductivities higher than expected for clay soils (Ogden et al., 2013).

In 2008 the Smithsonian Tropical Research Institute (STRI) established the interdisciplinary Agua Salud Project to improve understanding of ecosystem services provided by seasonal tropical forests affected by land use and climate change with a major focus on water resources (Stallard et al., 2010). These data have been used to test hypotheses related to the effects of land cover and land use on runoff generation in the humid tropics. Ogden et al. (2013) found forested landcovers generated smaller peak storm flows and increased dry season baseflow compared to degraded pasture. Cheng et al. (2017, 2018) used these data to test alternative models of preferential flow in a distributed hydrological model. Litt et al. (2015) and Gardner et al. (2017) used these data to inform storm event hydrograph separation models. Adamowicz et al. (2019) used these to data quantify the effectiveness of payments for ecosystem services schemes in tropical catchments.

These data include observations of volumetric discharge and rainfall over 13 experimental catchments summarized in Table 1. Figure 1 shows a map of the catchments with predominant landcovers as of 2008. We assigned numbers to the weirs for use by field technicians and a three character site code that abbreviates a more colloquial description. The largest catchment instrumented, the Río Agua Salud catchment (RAS) has an area of 1,313 ha that includes the main stem of the Agua Salud River and consists of multiple land uses including secondary forest of various ages and rotational grazed pasture. The RAS catchment is a subcatchment of the Panama Canal Watershed that drains into Lake Gatun which is part of the Panama Canal. The RAS catchment includes the mature forest (FOR), forest-pasture mosaic (MOS), pasture (PAS), and Arnulfo (ARN) subcatchments. These subcatchments and the remaining catchments outside the RAS range in size from 6.0 ha to 183.0 ha.

The mature forest catchment (FOR) is a tributary to RAS and consists of secondary forest at least 34 years old with 80% consisting of forest that is at least 80 years old (Ogden et al., 2013). The forest-pasture mosaic (MOS) catchment is a tributary of the RAS that includes more than 50% older forest (>15 years), 30% young forest (<15 years), and 20% active cattle pasture (Ogden et al., 2013). The teak plantation (*Tectona grandis*) catchment (TEK) contained a young forest (<5 years) prior to 2008 and includes an upstream catchment consisting of 25 year old secondary forest (TKU) (Weber and Hall, 2009). Site managers interplanted native species among the teak plantation in 2016.

Site managers replaced a failed shade coffee plantation (COF) with a silvopastoral system that follows the Panama Canal Authority standard practices. The silvopastoral system includes traditional pasture grasses with improved pasture grasses that remain productive well into the dry season. Managers also fenced riverine or gallery forest and planted pasture trees to provide additional fodder and shade for cattle. The native species plantation (NAT) consists of 21 treatments arranged in mixtures and monocultures to test various hypotheses related to the growth and development of native timber species (Weber and Hall, 2009). Managers established the secondary succession catchment (SEC) on land with 1 year old secondary forest. The SEC catchment was an actively grazed cattle pasture prior to 2007 (Weber and Hall, 2009). The pasture catchment (PAS) contains mostly rotationally grazed cattle pasture with approximately 15.5 ha of sparse young gallery forest (Ogden et al., 2013).

The *Saccharum spontaneum* catchment (SAC) consists primarily of an introduced invasive grass that covers three percent of the Panama Canal Basin. *Saccharum spontaneum* establishes in pastures and agricultural fields and is maintained by fire (Saltonstall et al., 2012). A recent fire history is included in Boeschoten et al. (2020). The cut catchment (CUT) consists of young secondary forest with a small patch that was cut and burned in 2018. The downstream cut catchment (CTD) contains both CUT and a larger 30 year old secondary forest. The Arnulfo catchment (ARN) consists entirely of old (>80 years) secondary forest (Bretfield et al., 2018).

3.0 Hydrologic Instrumentation and Measurements

The United States Panama Canal Commission constructed research infrastructure on the Agua Salud River in 1979 to measure streamflow and meteorological variables (U.S. PCC, 1983) as part of a study aimed at conceptual model testing and a preliminary examination of the effects of deforestation on streamflow. Installed infrastructure included three large short-crested concrete weirs of the USDA Agricultural Research Service design on the main stem of the Agua Salud River and on two tributaries. The design of these weirs included a concrete box with a steel-plate sharp-crested weir that caught the entirety of the flow over the short-crested weir at low flows (< 0.03 m^3 s^{-1}). The report describing the original 1979-1980 study noted factors that negatively affected data quality including difficult site access, frequent partial plugging of weirs by woody debris, and difficulties with operating data collection equipment in the tropics (U.S. PCC, 1983). These issues continue to the present day and have required significant processing to address.

3.1 Rainfall

We measured rainfall using clusters of tipping bucket rain gages from a variety of vendors installed at several sites in the study area. HOBO Pendant® Data Loggers (Onset Computer Corp., Bourne, MA, USA) attached to each rain gage recorded tips. Initial gage clusters consisted of two redundant rain gages. We added a third or fourth gage to each cluster to reduce the impact of plugging, fouling or data logger malfunction as the project progressed. Using the methods found in Ciach (2003) resulted in a mean standard error of ±0.0353 mm for a single 15-minute accumulated rainfall value from a tipping bucket rain gage with a bucket size of 0.254 mm. Figure 2 shows a typical rain gage cluster.

3.2 Volumetric Discharge

Field technicians deployed non-vented pressure transducers with Level TROLL® Data Loggers (In-Situ Inc., Fort Collins, CO, USA) to record water level measurements behind weirs. A separate BaroTROLL® Data Logger (In-Situ Inc., Fort Collins, CO, USA) deployed in a vented enclosure near the project site collected atmospheric pressure data that we used to adjust effects of atmospheric pressure variations on water level measurements. We deployed water level data loggers in a steel enclosure anchored to the side wall in low-flow weir boxes. We installed pressure transducers in housings attached to a steel post driven into the stream bed 1-2 m upstream from high flow weirs away from the water surface area affected by the weir. Approximately monthly, field technicians made manual measurements of water depth using a staff-gage. We assumed a standard error for stage measurements of ±7.75 mm based on the published uncertainty of the pressure transducers and the consistency of staff-gage depth measurements in the field. Using this standard error with the weir equation published in Ogden et al. (2017) resulted in an approximate discharge standard error of ±(0.02 * Q + 0.000519 $m^3 s^{-1}$) for 5-minute discharge measurements where Q is discharge in $m^3 s^{-1}$. A typical project weir showing the two-stage design is shown in Figure 3.

3.3 Data Processing

3.3.1 Rainfall

Processing rain gage bucket tips for each rain gage cluster involved the following steps:

1. Time Correction. Incorrect field laptop settings resulted in timing errors. We used graphical plotting software to visually inspect each rainfall record and manually adjust the time. This process included data from other clusters in the network and from the Panama Canal Authority meteorological network.
2. Storm event isolation. We produced a series of isolated storm events for each gage in the cluster. We defined a storm event as a period of continuous rainfall with less than 3 hours of rainfall cessation between any measurement. We found under-reporting was more common than over-reporting. We constructed a final storm event record by using data from the gage with the largest storm event total in a gage cluster.
3. The rain gage tipping bucket data logger recorded a time for each tip. We accumulated rain gage tips into 15-minute periods. We converted the final storm event record to a record of 15-minute accumulated rainfall.

These data also include spatially aggregated rainfall for each catchment computed using interpolation by Universal Kriging. We generated interpolated data for each 15-minute period during which at least 3 clusters in the gage network reported data.

3.3.2 Volumetric Discharge

Processing volumetric discharge from each catchment involved the following steps:

1. Concatenation of individual records of water pressure using a commercially available time series data editor.
2. Correction of timing errors due to incorrect laptop clock errors. We used a time series data editor to compare records of water pressure to rainfall records and discharge from nearby catchments to identify and correct timing errors.
3. Barometric correction using barometric pressure data to remove pressure fluctuations from records of water pressure.

4. Convert absolute pressure to water depth above the weir using manual field measurements of depth.
5. Employ time series decomposition to correct systematic errors in the stage record due to weir clogs resulting from woody debris and sensor drift. This method uses time series analysis to isolate and preserve storm event discharge while correcting baseflow when clogs are most common. These data include both processed and unprocessed stage data.
6. Apply rating equations found in Ogden et al. (2017) to convert corrected and adjusted water stage time series to discharge. The weirs at the RAS, FOR, and MOS catchments are fully sedimented. We used the modified discharge coefficients found in Ogden et al. (2017) to account for the effects of sedimentation.

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Data Availability

These data are publicly available at Regina et al. (2021) (https://www.hydroshare.org/resource/d3d7eca5f07048d499b4cffb2aec7750/). The processed data are contained in three separate Hierarchical Data Format 5 (HDF5) (The HDF Group, 2020) archives (.h5 files) and one zip archive containing compressed comma separated values (.csv). We found the HDF5 format was appropriate for serving millions of hydrometric measurements. The .h5 files include a five-minute discharge time series file, a five-minute stage time series file, and a 15-minute gaged and interpolated rainfall file. The stage and discharge files include data processed using time series decomposition. HDF5 files contain a hierarchical data structure organized into "groups" and "datasets." HDF5 groups are conceptually similar to file system folders. HDF5 datasets are analogous to files. HDF5 files can be explored using a variety of tools, the most common of which are HDFView and h5dump (https://www.hdfgroup.org/downloads/). These data can also be accessed through application programming interfaces (APIs) in a variety of programming languages including Python, Java, C, and C++. We include Python scripts for extracting the data to CSV format through a command line interface which does not require programming knowledge, but does require familiarity with command line interfaces and arguments. Refer to the README.md files that accompany the data for a more complete description of the hierarchical structure and examples of how to extract the data. Raw and uncorrected versions of these data are also included as compressed archives. Raw rainfall data can be found with the Agua Salud Rainfall Data in the raw_rain_data.tar.xz file. Stage data that have not been corrected using time series decomposition can be found in the Agua Salud Stage Data as a raw_stage_data.tar.gz file. These unprocessed data include additional descriptions in README.md files.

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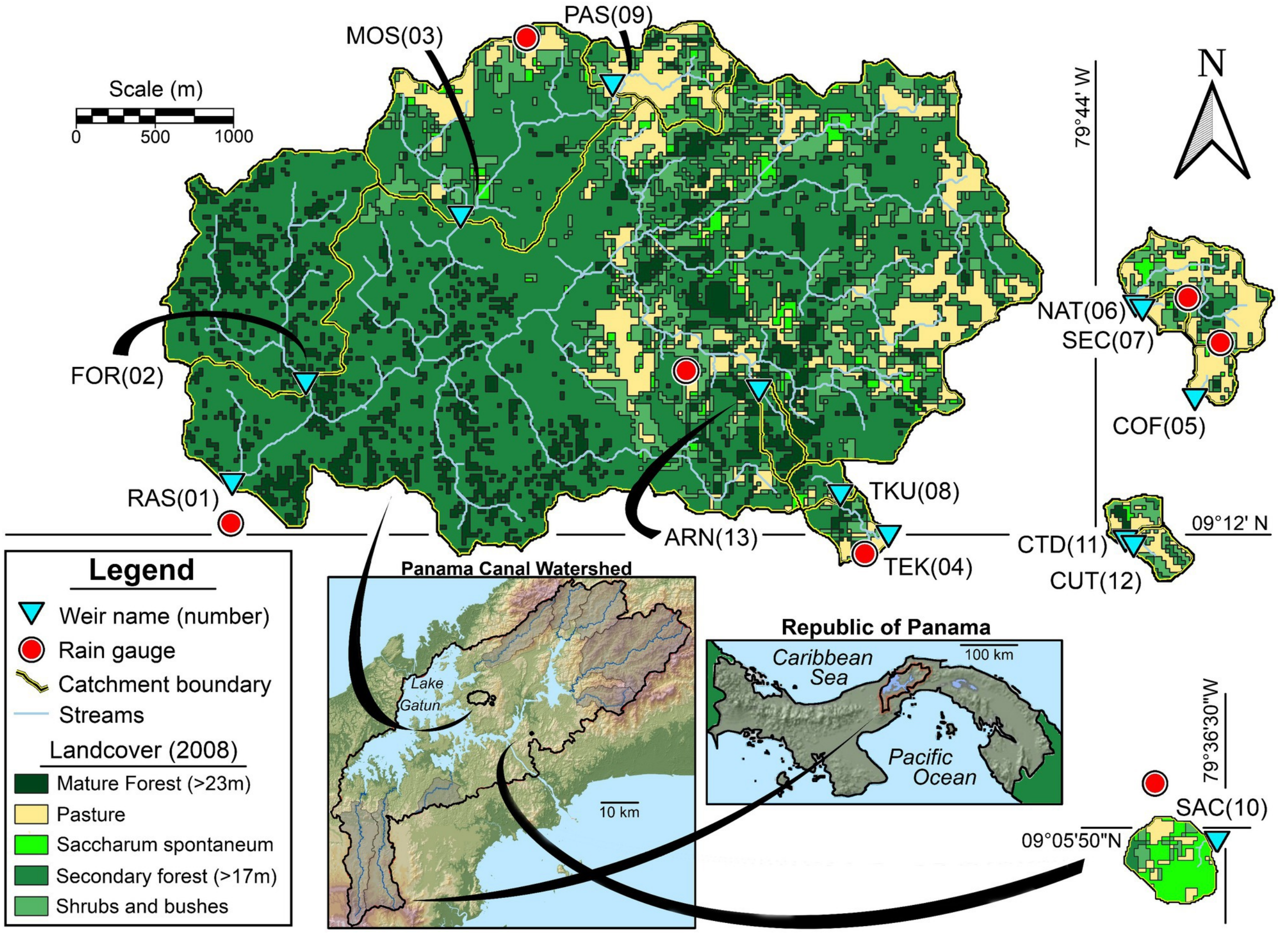

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Table 1. Catchment Descriptions. See Figure 1.

Number	**Site Code**	**Area (ha)**	**Description and land use history**
01	RAS	1313.6	Río Agua Salud, mixed land cover, downstream from 02, 03, 09, 13
02	FOR	144.0	Mostly 80 year or older secondary forest with some 25 year old secondary forest, upstream from 01
03	MOS	183.0	Mixture of secondary and old secondary forest and grazed pasture, upstream from 01, downstream from 09
04	TEK	22.7	Pre-2009 grazed secondary forest, 2009-2015 teak plantation. Since 2016 native species plantation, downstream from 08 without grazing
05	COF	9.4	Pre-2013(?) grazed secondary forest. Since 2013 silvopastoral treatment with rotational grazing.
06	NAT	43.7	Pre-2009, grazed secondary forest. Since 2009 native species plantation without grazing.
07	SEC	6.0	Pre-2009 grazed young secondary forest. Since 2007, secondary forest, no grazing since 2009.
08	TKU	9.2	25 year secondary forest, upstream from 04
09	PAS	42.4	Since before 2008, active cattle pasture. Rotational grazing since 2009 with manual clearing of brush. Upstream from 03
10	SAC	23.4	*Saccharum spontaneum* monoculture grassland
11	CTD	16.9	Since approx. 1990 forest, grazed before 2013? Downstream from 12
12	CUT	8.7	Since about 1990 forest grazed before 2013?, clear cut in 2018, regrowing secondary forest as of late 2020, upstream from 11
13	ARN	9.5	80+ year secondary forest, upstream from 01