WATER RESOURCES IMPACT

PANAMA CANAL WATERSHED EXPERIMENT: AGUA SALUD PROJECT

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The Agua Salud Project utilizes the Panama Canal's (Canal) central role in world commerce to focus global attention on the ecosystem services provided by tropical forests.

The Canal was one of the great engineering projects in the world. Completed in 1914, after almost a decade of concerted effort, its 80 km length greatly shortened the voyage between the Atlantic and Pacific Oceans. An entire class of ships, the Panamax, has been constructed to maximize the amount of cargo that can be carried in a Canal passage. In today's parlance, the Canal is a "green" operation, powered largely by water (Table 1). The locks, three pairs on each end with a net lift of 27 meters, are gravity fed. For each ton of cargo that is transferred from ocean to ocean, about 13 tons of water (m^3) are used. Lake Gatún forms much of the waterway in the Canal transect. Hydroelectricity is generated at the Gatún dam, whenever there is surplus water, and at Madden Dam (completed in 1936) when water is transferred from Lake Alhajuela to Lake Gatún. The Canal watershed is the source of drinking water for Panama City and Colon City, at either end of the Canal, and numerous towns in between.

Table 1. Panama Canal Average Water Budget.

	Annual Discharge $km^3\ yr^{-1}$	Average Discharge $m^3\ sec^{-1}$
Total Runoff	4.4	139
Lockages[1]	2.6	82
Hydroelectricity[2]	1.2	39
Drinking	0.27	9
L+H+D =	4.1	130
Total, 1982	3.3	105

[1]Thirty-seven per day at 191,000 cubic meters per lockage.
[2]Power generation is a buffer. When water is in short supply, electricity is either purchased from the power grid or generated on site using fossil fuels.

The Panama Canal Authority (ACP) manages all the water in the Canal Basin, focusing on the seasonality of supply. Enough water must be stored in the eight-month wet season (May to December) to provide for the four-month dry season (January to April). Unfortunately, the most intense rains of the year come at the end of the wet season, so the lakes cannot be topped off as quickly as possible, because some storage capacity has to be retained for late-wet-season floods, which could otherwise seriously damage Canal infrastructure. Topping the lakes off is done as late in the wet season as meteorological forecasts permit. Dry years present another problem, that of insufficient water in Lake Gatún, which leads to draft restrictions and reduced cargo crossings. Low water in Lake Alhajuela, can cause problems for drinking water supply. To conserve water in dry years, fossil fuels or electricity from the national power grid replace hydroelectricity.

The ACP is currently building a third set of locks for ships that are larger than the Panamax class, "Post-Panamax." These locks are also gravity fed, but have parallel holding basins to conserve water, thereby reducing water consumption per lockage by up to a half a lock-chamber volume. The idea is to increase the efficiency of water use from 1:13 to something better, allowing more of the available water to be used for transport.

About half of the Canal watershed has been deforested, and the official policy in the Canal watershed (Law 21) is to reforest in anticipation of regaining ecosystem services. Land cover and its manipulation can have collateral impacts – positive, negative, or unquantifiable. The positive impacts are referred to as "ecosystem services" – included are carbon storage, water quantity and quality, biodiversity, environmental resilience, and undiscovered pharmaceuticals. Some impacts are not positive – such as water wasting, soil erosion, landslides, wildfire, and extinctions. In parts of the watershed, reforestation is made particularly challenging by the invasion of a wild sugar cane (*Saccharum spontaneum*).

From November 2007 to present, we have planted over 150,000 trees and have mapped and described 108 0.1 ha plots in a 25-year chronosequence of secondary succession plots on our lands

Carbon fixation through photosynthesis by most terrestrial plants (a service) is directly linked through physiological mechanisms to water consumption (a tradeoff). Forests consume more water than other land covers, and when forests replace other types of vegetation runoff is typically reduced by 150 to 600 mm per year. This is a huge quantity of water from the perspective of water users, enough to completely dry up rivers in some regions undergoing reforestation.

In the Canal watershed, the use of lake water during the dry season is supplemented by groundwater baseflow derived from infiltration of water during the wet season. And indeed, the Canal has been a center of attention for the forest-versus-water controversy. Reports commissioned by the World Bank (see Calder *et al.*, 2001) assert that reforestation could be detrimental to the Canal. This conflict was featured by articles in the *Economist* [2005-04-21], and the *New York Times* [2005-05-25].

THE AGUA SALUD PROJECT

The Agua Salud Project (Project) (Figure 1) focuses on landscapes in the central Canal Basin, where many fundamental aspects of ecosystem services and costs can be rigorously quantified using landscape scale studies – hydrologic processes, the carbon cycle, biodiversity, rural economics, ecotourism, and impacts on global trade and investment. The region encompasses both protected mature forests and a wide variety of land uses that are typical of rural Panama. The Project involves parallel forestry, hydrology-biogeochemistry, and ecosystem-services economics initiatives that seek to describe processes in sufficient detail that they may be rigorously modeled for past, current, and future conditions and extrapolated, using available data sets, to the entire Canal Basin. We anticipate that our approach will be able to make predictions about novel states of a system or about new conditions, and should apply to the entire Canal Basin. At the same time, we ask about the implications of such predictions on the livelihood and economics of the Panama Canal basin, the country of Panama, and globally. One principal focus is on the tradeoff between growing trees and the consumption of water by those same trees.

The Project is currently funded through the HSBC Climate Partnership and is operated by the Smithsonian Tropical Research Institute (STRI) in close cooperation with the ACP, which has funded much of the reforestation and some of the meteorological work, and the Panama Environmental Authority (ANAM). Current core research collaborators include the U.S. Geological Survey (USGS), Institute of Geoecology University of Potsdam, Germany, and Department of Civil and Architectural Engineering, University of Wyoming.

We are undertaking catchment-scale experiments that include four types of reforestation treatments and three types of controls that serve to distinguish between effects of treatments and the effects of interannual and long-term climate variation. We ask (1) How do landscape treatments and management approaches such as carbon storage, water quality and quantity, dry-season water

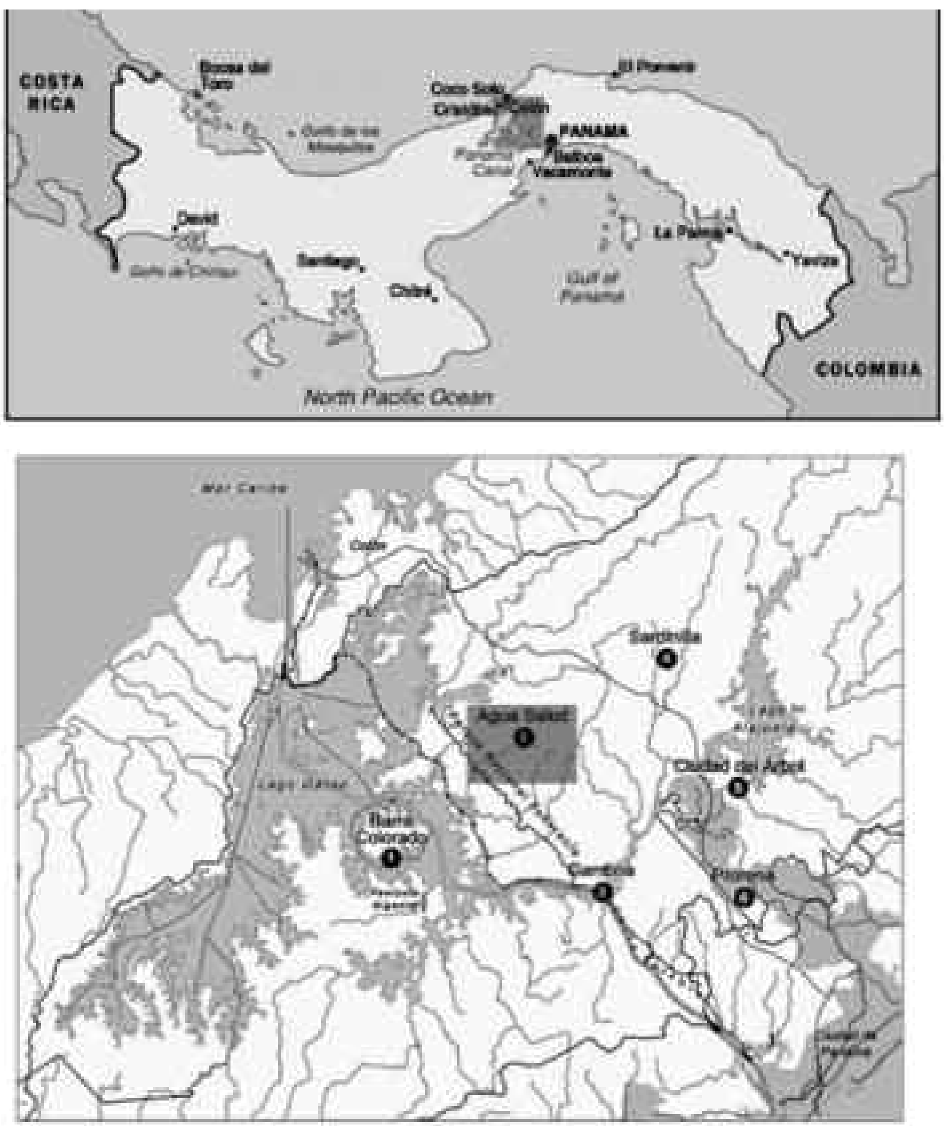

Figure 1. Site Map (Upper Panel) – Panama, gray rectangle indicates lower panel.

Lower Panel – Sites used in the Agua Salud Project.

1. **Barro Colorado** - A long-term research site of STRI, with two research catchments.

2. **Agua Salud** - gray rectangle, the primary research site for this project, a typical rural landscape with 650 ha of project lands on which 150,000 trees have been planted.

3. **Gamboa** - Site of STRI labs accessing the Agua Salud through Soberania National Park.

4. **Sardinilla** - Site of the McGill University Carbon Project, a biodiversity plantation of over 10,000 trees on former pasture..

5. **Ciudad del Arbol** - Site of an ACP - University of Panama native-species reforestation following *Saccharum spontaneum*.

6. **Prorena** - Site of a STRI native species reforestation following *S. spontaneum*.

supply, and biodiversity affect ecosystem services and costs? (2) Can management techniques be designed to optimize forest production along with ecosystem services and costs during reforestation? (3) Do different tree-planting treatments and landscape management approaches influence groundwater storage, thought to be critical to maintaining dry-season flow, thus ensuring the full operation of the Canal during droughts? (4) What are the biological, hydrological, and biogeochemical roles of fire in this landscape? Fire is a major component in the landscaping tool kit of the rural agriculturalist that also cements the dominance of the invasive wild sugar cane, (*Saccharum spontaneum*). (5) Can we identify treatment approaches, beyond conventional management, that can enhance desired ecosystem services? Additional work will also address biodiversity, social, and economic values of these forests.

At the Canal Basin scale, we ask (6) How are water and carbon processed for different major land covers, water covers, and land uses of the entire basin? and (7) What are the operative ecosystem services and costs at the scale of the entire Canal, and how do these relate to the population within the Canal Basin, the operation of the Canal locally and globally, and to the regional and national economy of Panama?

Although the Panama Canal Basin is only 3,313 km^2, we cannot hope to examine each land cover in detail across the entire region. The United States (U.S.) established a remarkable hydrologic infrastructure that is operated today by the ACP and STRI. Unparalleled, top quality mapping and hydrologic data go back to 1905 when the U.S. started measuring rainfall and river discharge. In 1934, many of the current Canal Basin headwater river gages were completed. The remaining river-gage network was completed in 1947, and the rain gage network added 18 sites in 1965. Now, the entire Canal basin is covered by a dense network of hydrological monitoring stations including about 30 river gages, 10 lake gages, more than 70 rain gages, 20 complete meteorological stations, and twice-daily weather balloon soundings, along with weather radar. High-quality topographic mapping data are available from multiple sources. Regular, quasi-annual assessments of Canal Basin land cover at a 30 m resolution are being produced by the ACP.

The plant and animal biodiversity of the Panama Canal Basin has been characterized by various environmental organizations, including STRI. The U.S. Agency for International Development (AID) funded STRI, in 1996, to assist the Panamanian government in setting up an environmental monitoring program in the Canal Basin, Canal Basin Monitoring Project (PMCC), with a focus on monitoring the effects of deforestation and urbanization. These data underlie all aspects of our study at the Canal Basin scale.

Two types of site-to-regional scaling will be implemented. One will be through the hydrologic network, going from small catchment scale studies through data-rich subbasins, on up to the entire Canal Basin. The other will use available mapping and remote sensing to scale from small terrestrial plot studies of soils and vegetation up to the trans-Isthmian region. Up-scaling requires 'physics-based' hydrologic models that are compartmentalized and connected in a realistic way. Each compartment endeavors to rigorously represent its physics, biology, and chemistry based on careful characterization through field observation and testing. Ecosystem service characterizations will be coupled to these models.

RESEARCH SETTING, THE AGUA SALUD PROJECT

Our hydrology experiments are at the scale of entire catchments, ranging from 8 to 400 ha, permitting complete water and carbon inventories and exchanges for different land uses. The experimental catchments consist of three treatments: native-species plantation, native second growth, and teak plantation. We will also maintain three types of control catchments: mature forest, pasture, and invasive grass (*Saccharum spontaneum* – canal grass). Controls serve to distinguish between effects of tree growth and interannual-climate variation. About 650 ha of degraded land have been purchased to ensure the long term stability of the experiment and allow replication of treatments. Over 400 soil samples taken across the project site show little variation in texture (over 95% are classified as clays) and color.

The Agua Salud research site was established in the early 1980s by the Meteorology and Hydrology Branch of the Panama Canal Comission (PCC) with the objective of determining whether flood peaks were reduced in forested compared to deforested landscapes. Three weirs were installed and data were collected; however, funding ended in 1983. The study was reactivated by the PCC from 1997 to 1999. In 2007, STRI was awarded five years of funding from the HSBC Climate Partnership, including $4M-$5M for the Agua Salud Project. The University of Wyoming, The University of Potsdam, STRI, the USGS, and U.S. Army Research Office provided additional funding for personnel and major equipment. Private donors bought the research land and have leased it to STRI for 20 years, extendable to 40. The ACP funded the native-species reforestation as part of their overall reforestation plans in the Panama Canal Basin and a full meteorological station to be part of their network. Private donors helped fund the teak plantation. The HSBC Climate Partnership funding ends on December 31, 2011.

From November 2007 to present, we have planted over 150,000 trees and have mapped and described 108 0.1 ha plots in a 25-year chronosequence of secondary succession plots on our lands. For hydrology, we have a network of 12 gaged catchments with weirs. We also have a raingage network, two eddy flux towers, one in forest and the other in a native species plantation, a surface-energy-balance station, and ten shallow groundwater monitoring wells. For hydrochemistry, we are sampling streamflow using automated samplers, rain, throughfall, overland flow, and groundwater. In 2009, core staff hiring was completed. With 2010, the hydrochemistry lab is being completed, and the Agua Salud research program is fully operational. Finally, we are attracting other research groups that are studying carbon modeling, biodiversity monitoring, microbial biology, and ecosystem services studies.

Studies completed to date include throughfall studies and soils analysis, a 25-year chronosequence in 108 secondary succession plots, and LiDAR overflights. Work in progress include above-ground and below-ground carbon analyses, monitoring of all hydrologic and meteorological variables, and tracer studies using both natural and introduced tracers, as well as observations of shallow subsurface flow using electrical resistivity tomography at the hillslope scale. We are also educating large numbers of undergraduate, graduate, and post-doctoral students in the important field of tropical hydrology in collaboration with Panamanian universities

REFERENCE

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TECHNICAL PAPERS

Deborah Elcock identifies an important potential future conflict between renewable energy production and water availability.

Leslie L. Orzetti *et al.*, test the efficacy of restored forest riparian buffers along streams in the Chesapeake Bay watershed. Their findings are consistent with the hypothesis that forest riparian buffers enhance instream habitat, water quality, and resulting benthic macroinvertebrate communities with noticeable improvements occurring within five to10 years postrestoration.

Lily House-Peters *et al.*, report spatial analysis techniques determined that although the water demand of a study area in Portland, OR as a whole is not sensitive to drought conditions, certain individual census blocks do respond with a higher magnitude of water use.

Nicholas A. Procopio reports neither historic nor current cranberry agricultural practices considerably influence flow regimes or the channel morphology of streams in the New Jersey Pinelands.

Scott T. Larned *et al.*, propose a four-step framework for analyzing longitudinal flow variation and exploring its ecological consequences.

Rosemary W.H. Carroll *et al.*, present an integrated surface water and groundwater model of Mason Valley, Nevada to replicate the movement of water throughout the different components of the demand side of water resources in the Walker River system.

Gavin Gong *et al.*, present a case study of a simple framework for utilizing streamflow forecasts that works within an existing management structure.

Jaepil Cho *et al.*, examine how the SWAT model is responsive to riparian filter strip width and critical source area in modeling sediment and nutrient yields.

A full Table of Contents may be viewed at http://www.blackwell-synergy.com/toc/jawr/46/3

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