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SPRING DISCHARGE MONITORING IN LOW-RESOURCE SETTINGS: A CASE STUDY OF CONCEPCIÓN CHIQUIRICHAPA, GUATEMALA

Stephanie C. Tubman
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SPRING DISCHARGE MONITORING IN LOW-RESOURCE SETTINGS:
A CASE STUDY OF CONCEPCIÓN CHIQUIRICHAPA, GUATEMALA

By

Stephanie C. Tubman

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Geology

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2013

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This report has been approved in partial fulfillment of the requirements for the Degree of
MASTER OF SCIENCE in Geology.

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PREFACE

This work arose out of my assignment as a Peace Corps Volunteer in Concepción Chiquirichapa, Guatemala through the Peace Corps Master's International program in Geology.

While there were definite setbacks in collecting data in the field, the real limitations of the data I collected became apparent after returning to campus. In order to complement the limited analyses that were possible with the data, I conducted a review of methodologies and considerations for measuring spring discharge in settings with limited economic resources. I present this review in Chapter 1 both as a standalone guide and as background information to the study.

In Chapter 2, I present the methods used to collect and analyze the data, the limited results of the data, discussion of study limitations, and recommendations for future studies of similar scope. The intention is that this report serve as a guide to those conducting studies of spring discharge, in particular future Peace Corps Master's International students and others working in intercultural settings with limited economic resources.

ACKNOWLEDGEMENTS

This report would not have been possible without my colleagues in the Municipality of Concepción Chiquirichapa, in particular Marcelino Rivera, Coordinator of the Department of Protected Areas and Environment. He dedicated considerable time to field visits, as did park guards Eliberto, Daniel, and Rafael, and municipal plumbers Don Florencio and Don Anibal. The US Peace Corps and NSF PIRE Grant 0530109 provided the financial support for this work.

I am indebted to Bertha, Wilma, and Irma for their friendship, and to all those who welcomed me into their lives in the biggest and smallest ways during my two years in Concepción. Thank you also to Claudio Castañado at INSIVUMEH for his prompt attention to my requests for climate data.

This report would also not have been possible without the ideas and encouragement of my advisor, Dr. John Gierke. I also thank my committee members, Dr. David Watkins and Dr. Eric Seagren, for their time and constructive criticism, and the many professors from whom I've learned during my time at Michigan Tech.

Thanks to many friends and colleagues of the Michigan Tech PCMI and GMES communities, both in the Keweenaw and abroad. It's an honor to belong to such a dynamic and engaging group of people.

Thanks also to Mom, Dad, Seth, and my grandparents Esther, Donald Sr., and Roy, for giving me their blessing to go on a four-year adventure to the uncharted territory of the north and south. Special thanks are due to Grandma Marge, who always had faith in me, and Rüdiger, for everything!

ABSTRACT

Water springs are the principal source of water for many localities in Central America, including the municipality of Concepción Chiquirichapa in the Western Highlands of Guatemala. Long-term monitoring records are critical for informed water management as well as resource forecasting, though data are scarce and monitoring in low-resource settings presents special challenges. Spring discharge was monitored monthly in six municipal springs during the author's Peace Corps assignment, from May 2011 to March 2012, and water level height was monitored in two spring boxes over the same time period using automated water-level loggers. The intention of this approach was to circumvent the need for frequent and time-intensive manual measurement by identifying a fixed relationship between discharge and water level.

No such relationship was identified, but the water level record reveals that spring yield increased for four months following Tropical Depression 12E in October 2011. This suggests that the relationship between extreme precipitation events and long-term water spring yields in Concepción should be examined further. These limited discharge data also indicate that aquifer baseflow recession and catchment water balance could be successfully characterized if a long-term discharge record were established.

This study also presents technical and social considerations for selecting a methodology for spring discharge measurement and highlights the importance of local interest in conducting successful community-based research in intercultural low-resource settings.

1 TECHNICAL REVIEW OF SPRING DISCHARGE MONITORING IN LOW-RESOURCE SETTINGS

1.1 SCOPE AND AUDIENCE

This technical review is targeted toward water resource technicians working in lower-income areas who have recognized a local need for short-term or long-term spring discharge monitoring. The objectives of this review are to: (1) outline general considerations for the implementation of spring discharge measurement in natural springs in lower-income areas, and (2) summarize specific methodologies for discharge measurement that may be appropriate in such settings.

It is meant to assist in the initial assessment of spring discharge monitoring feasibility in lower-income areas given unique hydraulic, economic, and social constraints. The technical information in this document is meant to provide a general orientation and is targeted toward those without special expertise in hydraulics or discharge monitoring. The social considerations presented herein may be useful to any technician operating in a cultural context distinct from his own, though these considerations are especially geared toward Peace Corps Master's International students.

1.2 INTRODUCTION

At the intersection of groundwater and surface water, natural springs are a significant source of water for people around the world. Where springs are available, they are often one of the most cost-effective ways to provide relatively pure water for consumption, hygiene, and irrigation. In Central America, surface water is often severely contaminated by solid wastes and agricultural runoff, and drilled wells can be prohibitively expensive (Losilla 2001). As household, agricultural, and industrial water demands increase with worldwide growth in population and consumption, well-informed water resource management is all the more pressing.

There are many methodologies that have been developed both in the field and in industrial applications for measuring water discharge under a variety of flow conditions. In lower-income areas, however, many of these methodologies can be too costly or maintenance-intensive to implement. Additionally, springs are sometimes engineered for protection and distribution from source to end user without thought to discharge monitoring, making flow difficult to access by simple means. The challenge in lower-income areas is to identify those methodologies that can be applied given local hydraulic, economic, and social constraints.

One of the key questions for water resource managers is how discharge will vary over time, and discharge monitoring is fundamental for understanding that variability. While variability is ultimately the result of changes in recharge or aquifer structure, recharge and aquifer structure are challenging to observe directly. In contrast, spring discharge itself is usually accessible plainly on the surface. Therefore, variation in discharge can be used to understand variations in recharge and aquifer characteristics, even when recharge and the aquifer cannot be observed directly (Bredehoeft 2007, Kormaz 1990, Manga 2001).

On a basic level, a record of discharge is important for identifying long-term trends and understanding general seasonal water availability. This knowledge of supply variation is necessary

to design effective systems for spring capture and distribution (Fry 2004). In combination with data on seasonal water demand, general knowledge of supply variation is fundamental for seasonal and long-range efforts at water conservation.

More rigorous analysis of spring discharge with climate data can provide important insight into the way the aquifer stores and transmits water. Recession analysis is used with discharge time series (spring hydrographs) to determine the rate at which heavy flow during precipitation returns to base levels when there is no precipitation. This analysis can reveal important aquifer properties such as hydraulic conductivity and specific yield (Amit et al. 2002, Dewandel 2003, Malvicini et al. 2005). In highly responsive aquifers, cross-correlation of precipitation and discharge time series can also reveal lag times between precipitation and discharge (Padilla and Pulido-Bosch 1995). In simple aquifers, both of these analyses may facilitate short-term forecasting of water availability.

Long-term discharge data is also necessary for the construction and validation of water balance models. In complex settings, water balance models provide a more robust method of predicting resource availability as they account explicitly both for aquifer storage and intervening root zone processes. The water balance model is founded on the idea that inputs (precipitation- P) and outputs (discharge- Q, evapotranspiration-ET) into a watershed must be equal, with the exception of changes in storage (ΔS). Assuming no groundwater flow in or out, this relationship can be expressed as:

$$P = Q + ET + \Delta S$$

Precipitation and discharge can be measured directly, and evapotranspiration can be modeled based on equations proposed by Thornthwaite and Mather (1955) for the root zone of a catchment. The Thornthwaite-Mather water balance assumes no storage and requires only inputs of precipitation, temperature, soil field capacity and root zone depth. In practice, many aquifers have a storage component that produces baseflow even when there is no precipitation. In this case, recession analysis of discharge data is important to create a meaningful water balance that accounts for aquifer storage (Wittenberg and Sivapalan 1999).

In lower-resource settings, water balance models may be useful for prediction of future water availability. Water balance models have application both for predicting short-term discharge based on recent precipitation (Alley 1985) and to predict water availability under long-range climate and land use scenarios (Jiang et al. 2007). The water balance may also be useful in determining spring recharge area (Bonacci and Magdalenic 1993). In small mountainous catchments, this can assist in the localization and subsequent protection of those recharge areas. See Xu and Singh (1998) for a thorough review of water balance models.

1.3 CONSIDERATIONS FOR SELECTING A METHODOLOGY FOR SPRING DISCHARGE MEASUREMENT

1.3.1 Technical Considerations

1.3.1.1 Improved Spring Sources

The first broad consideration for physical configuration is whether the water spring source is improved or unimproved. Springs are often captured for distribution of running water to storage tanks or individual households in the interest of convenience, water quality protection, and public health (Fry 2004). Direct physical measurement of spring discharge is not always possible in spring protection systems designed principally for the purposes of flow transport and water quality protection.

Where springs are already captured, it is necessary to evaluate the feasibility of different measurement methodologies according to water system design. Flow may be diverted from an open spring pond into a distribution pipe or channel, or the spring source may be covered and diverted through a closed piping system from source to end user.

While it is preferable to measure as close to the spring source as possible to avoid potential leakages, a downstream measurement may be the most practical option if the flow line includes junction boxes or other pressure breaks and direct measurement is not possible at the spring source itself. In cases where the flow line is completely closed, direct volumetric measurement may not be possible.

The flow line (including the spring source, junction boxes, and pressure breaks) should be surveyed with local people who have worked closely in its installation or maintenance. It is important to ask these informants focused questions about flow path, junction boxes, and other pressure breaks, verifying that information has been mutually understood if there is a language barrier present.

Once the flow line has been surveyed, it is possible to identify whether direct volumetric discharge measurement will be possible. Where volumetric measurement is not possible, available methodologies will depend on characterization of flow into two principal categories: open channel flow and closed channel/full pipe flow. Open channel flow has a free surface to the atmosphere. Closed channel flow occurs in a completely full conduit flowing under hydraulic pressure.

The methodology chosen will also depend on the magnitude of flow rate and conduit size. For high flow rates or where inlets or outlets are difficult to access, accurate direct measurement may be physically challenging. If a particular method may not be easily repeatable over the possible range of discharges, it is wise to employ multiple methodologies for comparison. Where financially feasible and where there is sufficient local interest in discharge monitoring, systems may also be retrofitted to allow for easier or more accurate measurement.

1.3.1.2 Unimproved Spring Sources

It may be possible to measure discharge without permanently engineering an unimproved spring source. This will depend on spring size, configuration, and the accuracy of measurement required.

For small or medium-magnitude springs, it may be possible to dam the spring and divert flow using a pipe or channel into a container for direct volumetric measurement (Anderson 1937). If people use the water source, the water may already be dammed in some way.

In smaller unimproved spring sources, a weir may be appropriate. If unimproved spring sources have high discharge and flow into an open channel, it may also be feasible to apply the stream area/velocity method. Where channels are very steep or irregular, chemical tracing could be an option provided that appropriate equipment and competent personnel are available.

It is important to note that where there is a project in progress to improve the spring source for distribution and protection from contamination, elements should be incorporated into the design to allow for easy and accurate spring discharge measurement. Where possible, it is easier to design and construct than it is to retrofit or adapt methods. See Fry (2004) and Milhelcic et al. (2009) for resources on the construction of spring protection boxes.

1.3.2 Social Considerations

It is important that the selected method be appropriate given the local context and goals of the organization implementing discharge measurements. Among the most important considerations are user friendliness, cost, security, and required frequency of measurement.

1.3.2.1 User Friendliness

If the long-term goal is to establish local monitoring, the method must be understandable to those helping with measurement and repeatable by them within the required degree of accuracy. Local counterparts may have pre-conceived ideas about measurement, may not fully understand explanations due to language or cultural barriers, or may not want to admit discomfort with a methodology. It is important to observe and double-check the accuracy and precision of counterpart measurements until comfort level is established, rather than assuming that they are comfortable with a particular methodology and will implement it correctly.

1.3.2.2 Cost

In lower-income areas, cost will be a restricting factor. Many manual measurement techniques require only simple materials. While they may be more labor intensive in some cases, they are likely to be more appropriate than costly electrical instrumentation.

1.3.2.3 Security

Where there is public access, the ability to secure costly equipment from theft and vandalism should be an important consideration. Vandalism and theft is less likely in small communities where local technicians are well-known and respected, but precautions should always be taken.

Even when installing simple structures, the practitioner should assume there will be theft or vandalism. If structures cannot be secured, the practitioner should be certain to document the set-up fully for future replacement.

1.3.2.4 Human Resources

Another consideration in the selection of a methodology is the frequency with which measurements must be made. One downside to manual measurement is that it will require a significant time commitment on the part of local stakeholders, especially when daily or weekly measurement is necessary. Some methodologies are more time-intensive than others, and it may be desirable to minimize the time commitment where possible. Where local counterparts are paid to maintain and monitor springs, or have a strong interest in discharge monitoring, this will not present as much of a concern.

1.4 METHODOLOGIES FOR SPRING DISCHARGE MEASUREMENT

Field conditions are rarely ideal. As such, the selection of methodologies may involve significant creativity and trouble-shooting on the part of field technicians. Methodologies should be thoroughly tested and error analysis conducted from the beginning in order to set standard procedure, understand measurement limitations, and catch correctable user errors. Flow conditions may also change significantly throughout the season, requiring adaptation at different times of year.

1.4.1 Timed Volume Methodologies

1.4.1.1 Container / Stopwatch

Where flow (Q) can be captured into a container of known volume (V), one of the most straightforward methodologies for determining discharge is to time (t) the filling of the container and calculate flow using the discharge equation:

$$Q=V/t \quad (1.1)$$

This method is commonly employed at discharge pipes or other places where flow can be captured into a container. It is simple and accurate at lower discharge rates. It can be accurate at higher discharge rates as well depending on the geometry of the discharge pipe, though it may not be possible to capture flow adequately at higher discharges. It also will not work where outflow pipes are submerged.

1.4.1.2 Filling Time Method

Discharge can be determined by measuring the volume of water accumulated in a tank over a certain amount of time. This method is applicable where spring flow enters a tank that has an outflow valve that can be closed in order to allow the tank to fill, or where such a valve can be installed retroactively.

The initial water level must be noted before closing the outflow valve, and the final water level noted before re-opening the outflow valve. The dimensions of the inside of the tank must also be measured in order to obtain the volume of fill over the given time. Discharge is calculated using equation (1). The accuracy of this method will depend in part on the coordination of the technicians involved. It may not be viable for use with small tanks receiving high discharges.

1.4.2 Methodologies for Open Channel Hydraulics

Where direct volumetric measurement is impossible or unreliable, there are a number of hydraulic relationships that can be used to determine discharge with varying degrees of certainty. These relationships are discussed in detail in the following sections and include the area-velocity-discharge relationship, Manning's equation, and the Darcy-Weisbach equation. The method applied will depend on channel geometry and flow characteristics: principally, whether flow is **open channel** or **closed conduit** (pressurized).

Open channel flow occurs when flow has a free surface. It most commonly occurs in open-air channels of various scales, both man-made and natural. It also occurs in pipes flowing partially full.

1.4.2.1 Stream Area/ Velocity Methods

Where spring discharge flows into an open stream or man-made channel, the stream area/velocity method is commonly employed to estimate discharge. This method is based on the discharge equation:

$$Q = v * A \quad (1.2)$$

$$\begin{aligned} Q &= \text{discharge (m}^3/\text{s)} \\ v &= \text{average flow velocity (m/s)} \\ A &= \text{cross-sectional area of flow (m}^2\text{)} \end{aligned}$$

The channel section selected for measurement should be long enough to allow for confident timing of float movement; one source suggests at least 3 m (Brown 2006). The method assumes steady and uniform flow over the measurement period. While natural channels will rarely fit ideal conditions, it is important that the channel section have relatively constant profile and slope over the section to be measured. It is also important that the channel have enough depth that objects on the channel bottom do not affect velocity throughout the flow profile (Dodge 2001).

1.4.2.1.1 Determining cross-sectional area

Where channel morphology varies in the direction of flow, at least three cross-sections perpendicular to flow should be measured along the channel section. The average cross-sectional area of flow is determined by dividing the cross-section into sections and determining average channel depth across each section. If the channel bottom is relatively flat, 3-5 depth measurements may be sufficient. Where it is very irregular, more depth measurements should be taken (Brown 2006, Dodge 2001). In practice, time and personnel constraints may limit these measurements.

1.4.2.1.2 Determining velocity

1.4.2.1.2.1 1. Float Method

The float method is likely to be most accessible, though its accuracy is limited. Where there is significant wind, large ripples, or back currents on the channel, the method will be considerably less accurate.

In this method, floats should be released above the first cross-sectional transect and their path should be timed from that transect to the last. This should be repeated along each of the averaged channel depth sections if possible, with three trials along each line (Brown 2006). As flow velocity will vary from flow surface to bottom of the channel, the averaged surface velocity should be multiplied by a correction coefficient (see Table 1) depending on the depth of the channel where the float velocity has been measured.

Table 1. Correction coefficients for float velocity based on channel depth. Reproduced from Dodge (2001), p. 13-5.

| Average depth (ft) | Correction Coefficient |
|--------------------|------------------------|
| 1 | 0.66 |
| 2 | 0.68 |
| 3 | 0.70 |
| 4 | 0.72 |
| 5 | 0.74 |
| 6 | 0.76 |
| 9 | 0.77 |
| 12 | 0.78 |
| 15 | 0.79 |
| >20 | 0.80 |

The *Water Measurement Manual* (Dodge 2001) reports that weighted rods can also be used as floats. These are designed to float upright with the bottom end travelling at approximately 90% of the total channel depth. The method presumes that a rod will move close to the mean velocity across the velocity profile along which it is travelling. While this method would require some local design and experimentation, it may be useful for comparison with surface float velocities.

2. Integrating (Rising) Float Method

The integrating float method involves releasing a buoyant object from the channel bottom and measuring the time it takes to rise and the horizontal distance it travels from release point to surface, which depends on velocity throughout the flow profile. This method is based on the assumption that flow is steady and uniform, the float is infinitely small, and the float rises at a constant velocity, travelling at the horizontal stream velocity as it rises (Liu 1970).

To comply with the float criteria, small lightweight floats (< 4 cm) should be used. The greater vertical distance it takes the float to reach its upward terminal velocity as a percentage of channel depth, the greater the error introduced (Liu 1970). At the same time, floats must be large enough to spot upon surfacing and recover, if necessary.

As with the surface float method, the rising float should be released multiple times across various sections of the channel to calculate an average velocity:

$$v = L / t \quad (1.3)$$

L=horizontal path length from release to surface (m)

t= time from release to surface (s)

In the laboratory and under controlled field conditions, this method can yield more accurate discharge measurements than with surface floats. Practically, it may be difficult to release the float from the same location repeatedly, spot the float at the surface, or measure the float's horizontal path length accurately.

3. Manning's Equation

The velocity of open channel flow can also be estimated using Manning's equation (Chanson 2004; Gioia and Bombardelli 2002). This requires measurement of the water surface slope and an estimate of channel roughness, as well as measurement of cross-sectional area of flow:

$$v = k/n (A/P)^{2/3} s^{1/2} \quad (1.4)$$

v = velocity (m/s)

k = conversion factor ($1 \text{ m}^{1/3} / \text{s}$ for metric system)

n = Manning's roughness coefficient

s = slope of water surface (m/m)

A = cross-sectional area of flow (m^2)

P = wetted perimeter of flow (m)

[note: $A/P = R_h$, hydraulic radius]

Cross-sectional area should be determined as in the direct area-velocity method, and wetted flow perimeter can be derived from these same measurements. Slope may be estimated by installing two rulers or height gages fixed to a common datum, one upstream and one downstream, and measuring the difference in water level (Chaskar 2013).

$$\text{Slope} = \text{Rise/Run} \quad (1.5)$$

Slope can also be roughly estimated using a carpenter's level or clinometer. In some areas, slope may be gradual and precise equipment will be unavailable. These factors may make accurate slope measurement challenging. The equation offers an approximation only.

Even if channel geometry is well constrained, Manning's roughness coefficient is difficult to estimate for natural or dilapidated channels. The equation should be used for comparison with other methods, or where there are no other options. The following table offers some common values of Manning's coefficient:

Table 2. Manning's roughness coefficients by channel material for stable channels. Reproduced from Chanson (2004) (§) and Arcement and Schneider (1990) ().*

| Channel Lining | | Roughness Coefficient (n) | |
|-------------------|-------------|---------------------------|--------------------|
| Glass and plastic | | 0.010 [§] | |
| Planed wood | | 0.012 [§] | |
| Unplaned wood | | 0.013 [§] | |
| Concrete | Finished | 0.012- 0.018* | 0.012 [§] |
| | Unfinished | | 0.014 [§] |
| Earth | Firm Soil | 0.025 [§] | 0.025- 0.032* |
| | Coarse Sand | | 0.026- 0.035* |
| Gravel | Fine Gravel | 0.029 [§] | 0.024* |
| | Gravel | | 0.028- 0.035* |

| | | | |
|--|---------------------------|--|-------------------|
| | Coarse Gravel | | 0.026* |
| | Cobble | | 0.030-0.050* |
| | Boulder | | 0.040-0.070* |
| | Flood plain (light brush) | | 0.05 ^s |
| | Flood plain (trees) | | 0.15 ^s |

Consult Arcement and Schneider (1990) for more information on selecting an appropriate Manning's roughness coefficient, including in dynamic channels.

4. Instrumentation

Current meters and acoustic velocity meters are often used in industry for open channel velocity measurement and can produce very accurate measurements when properly calibrated and operated. These are likely to be inappropriate for use in lower-income areas, however, because they are prohibitively expensive (upwards of \$600-1000 per unit) and require extensive operator training. If already available, they may be practical for short-term use. For an overview on the operation of such instruments, consult Dodge (2001).

1.4.2.1.3 Stage/Discharge Ratings

At larger springs that flow into wide natural channels, velocity/area measurements can be time and resource-consuming. In those cases where long-term discharge monitoring is desirable, it may be practical to form a stage-discharge relationship to avoid frequent manual measurements (cf. Buchanan and Somers 1969). If conditions in the channel are steady and uniform over time, this relationship will allow a water height (stage) reading to be correlated with discharge.

To form the relationship, measurements must be made over as wide a range of discharges as possible (using the velocity/area or other appropriate method) and correlated with simultaneous stage measurements. Stage can be measured using a ruler or tape measure correlated to a fixed datum, or with a more professional staff gage (\$20-40). Due to vandalism, it is not advisable to leave a gage installed in areas with public access.

This method will be most useful in engineered channels with constant geometry. It will be less useful in natural channels where channel cross-section is likely to change due to erosion, deposition, and plant growth, or where upstream inputs may change (Buchanan 1969).

Pressure and ultrasonic depth sensors are useful in determining a frequent record of stage level. They can be simpler to operate and less expensive than open-channel velocity equipment. Even so, they are still likely to be out of budget, and need to be carefully protected against theft or vandalism.

1.4.2.2 Weirs

A weir may be practical where long-term discharge measurements are required and flow is already channeled into an open conduit such as a concrete channel or natural stream. Weirs are commonly built across channels to measure discharge or alter flow (e.g., to reduce turbulence).

Weirs measure discharge indirectly based on established relationships between discharge and water height above the bottom edge of the weir (crest).

Governing equations are derived from standardized geometries, requiring careful design, operation, and maintenance for accuracy. While weirs are not expensive to install or maintain, the technical requirements of their operation may present an obstacle to successfully monitoring discharge with them.

Weirs may be broad- or sharp-crested. Broad-crested weirs are commonly used for large stream discharges, and have the advantage that they can be submerged. Thin-plate weirs are limited to medium or small discharges, though their use is within the range of discharge of many natural springs. The most common thin-plate weir types are rectangular, triangular (V-notch), and trapezoidal (Cipoletti).

Water height (head) is always measured relative to the weir crest, with the crest as the zero datum. For accuracy, head measurement should be made at a distance upstream of the crest greater than four times the height of water above that crest (Brown 2006; Dodge 2001).

Regardless of shape, all thin-plate weirs must meet several conditions for use with established equations. If conditions are inadequate, accuracy may suffer considerably, and weirs should be reserved as a last resort option. The criteria given by Brown (2006) and Dodge (2001) are:

- Flow entering the weir must not have a velocity exceeding 0.1524 m/s, which can be tested using the methods outlined in section 3.2.1. Flow should be as uniform as possible. The minimum head above the crest should be 6 cm, or the required precision needed to distinguish between discharges may exceed the limitations of the head measurement. The water must flow freely over the weir crest without touching any part of the downstream face of the weir plate. The downstream water level should be at least 6 cm below the weir crest. Submerged weirs cannot be used with any accuracy.
- The weir plate itself must be installed vertically and normal to flow, with sharp edges. Ideally, the plate will be very thin (>2 mm), though if this is not possible, downstream edges should be beveled to 60 degrees to prevent water from adhering to the downstream face of the weir plate.

For smallest discharges, a 90-degree V-notch weir is appropriate. To produce full contraction, or curvature of the flow across the weir, certain conditions must apply. In addition to all of the conditions above, channel width should be at least 1 m, and the drop between the bottom tip of the notch to the channel bottom below should be at least 0.45 m. If these conditions are met, the weir is fully contracted and the following equation may be applied (Dodge 2001):

$$Q = 2.49 h^{2.50} \quad (1.6)$$

Q=discharge (ft³/s)
h=head above crest (ft)

For higher discharges, a rectangular weir may be appropriate. For full contraction, all general conditions must be met, the notch must be at least 15-cm wide, and the height of water on the weir

must be no more than one third the crest width. Where flow is fully contracted, the following equation can be applied (Dodge 2001):

$$Q = 3.33h^{3/2} * (L - 0.2h) \quad (1.7)$$

Q=discharge (ft³/s)
h=head above crest (ft)
L=length of the weir (ft)

Weir operators should be aware that weirs and gages installed in open-access areas will be subject to vandalism or theft unless well-secured. Metal weir plates may be especially vulnerable. General wear will also undermine the long-term consistency of measurements. Care should be taken to document weir geometry as it may need to be replaced at any time.

See Dodge (2001) for a full discussion on weirs, including their use under non-ideal conditions (for example, under partial contraction or with flow exceeding approach velocity).

1.4.2.3 Partially Flowing Pipes

When dealing with gravity-fed spring water distribution systems, one is likely to encounter partially flowing pipes. Spring flow may vary such that flow regimes may change from season to season or from year to year. In addition, many systems in lower-income areas may not be designed intentionally, allowing flow regimes to fluctuate regularly.

Partially flowing pipes present a unique challenge for open channel flow measurement when direct volumetric measurement or estimation is not possible. Unlike for closed (pressurized) pipe flow, knowledge of external pipe geometry is insufficient to calculate an estimate of discharge without also knowing the depth of flow within the pipe.

Manning's equation (Equation 4) may be used to estimate discharge where pipe slope can be measured and the depth of flow within the pipe can be observed at the outflow or inflow to estimate cross-sectional flow area.

In wide channels, Manning's roughness coefficient is approximately constant for a given type of lining. It should be noted, however, that the coefficient has been observed to vary significantly with depth of flow in partially flowing pipes (Camp 1946). Calculations should account for this variation; see Akgiray (2005) for more information.

Without knowing flow depth/cross-sectional flow area in the pipe, discharge cannot be estimated. Even so, the equation may still be used to provide a sense of the potential variability of flow given particular pipe geometry.

Measurement will be additionally complicated when the flow regime alternates between open and closed pipe flow. This may introduce air into the system and make it difficult to distinguish between the two conditions. While instrumentation exists that can measure both flow conditions (see Natarajan 1992), cost will be prohibitive in lower-income settings. Bachmann (2007) proposed an inline system for measuring channel flow in closed pipes using water level loggers. Cost and operational constraints will make this option inappropriate in many areas.

If flow falls freely at the outflow and both depth of flow and plume length can be measured, discharge can be estimated using tables derived from momentum analysis (see section 3.3.1).

1.4.3 Methodologies for Closed Channel Hydraulics

Full pipe or closed channel flow occurs in full conduits flowing under hydraulic pressure. At natural spring sources in lower-income areas, one is most likely to see closed channel flow in gravity-fed distribution systems. Practitioners should realize that systems in this context are likely to flow partially full at least some of the time. This will occur not only due to natural variations in spring flow from event-to-event or season-to-season but also due to inadequate engineering of distribution systems for local flow volumes. If partially full pipes are suspected, see section 3.2.4 for more information.

Technicians should be aware that where flow alternates between closed and open channel conditions, air can enter pipes and form pressure blockages. In some cases, conduits may appear to be full at the intake even though there is not uniform closed channel flow throughout the entire conduit. For this reason, it is important to employ multiple methodologies for estimating flow when direct volumetric measurement along the flow line is not possible.

As with partially full pipes, indirect measurement of closed channel flow can be challenging, though there are a few methodologies that may be appropriate.

1.4.3.1 Flow Geometry Analysis

Flow geometry analysis may be useful where flow falls in a free plume from an outflow, but is too cumbersome to measure volumetrically. In this case, discharge (Q – gpm) from full horizontal pipes may be estimated using the Purdue method (see Figure 1.1), which involves measuring the horizontal length of the plume jet relative to its curvature:

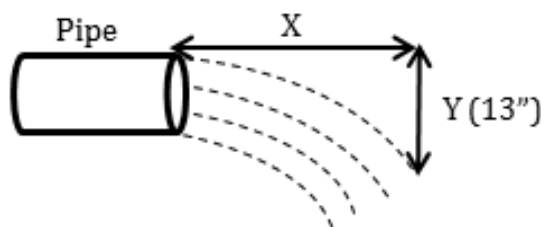
$$Q = 3.61 AX / Y^{1/2} \quad (1.8)$$

A = Cross-sectional area of horizontal discharge pipe (in²)

X = Horizontal distance from end of pipe to intersection with “Y” plumb line (in)

Y = Vertical distance between the top of the pipe and the top of plume curvature (in - tables typically present discharge values for $Y=13''$)

Figure 1.1. Schematic of flow geometry analysis (Purdue method) for estimating discharge from full pipes.



An inherent challenge of this method is achieving a stable measurement. The top curvature of the jet will oscillate, making it hard to maintain a stable “Y” distance. Measurement will be easiest with

a carpenter's square, if available, though measurement tools may be improvised as necessary. Due to differences between field and lab conditions, these equations will offer only rough estimates.

The Purdue methodology may also be applied to inclined and partially full horizontal pipes. A separate methodology derived from the observations of Lawrence and Braunworth (1906) exists for flow from vertical pipes. Several sources offer reference tables for all three conditions; see Brown (2006) or Hohn (2002).

1.4.3.2 Instrumentation

There is a variety of instrumentation that has been developed to quantify discharge from or within fully flowing pipes. Some instruments are installed in the flow line and others are installed at the end of the flow line. They can be divided into two categories: those that measure velocity and those that measure head differences.

In general, instrumentation is unlikely to have practical application in the field. At present, the most precise and functional equipment is expensive (USD\$250-1000+) and must be installed and operated under controlled conditions. Field calibration is necessary for many instruments, and if reliable methods exist for calibration, an instrument will provide little added utility in most cases.

If instruments are pre-calibrated and available for short-term use, they may be valuable for validation of other methodologies. This will depend on the specific instrument and adaptability to field conditions. Long-term installation of such equipment is unlikely to be useful unless local operators are highly motivated to use them and fully trained on their calibration and maintenance.

The most common velocity-sensing instruments are electromagnetic flow meters, acoustic meters (both Doppler and transit-time), rotameters, and propeller meters. Head measuring instruments include Venturi meters, orifice meters, and pitot tubes. Most of these instruments must be installed in-line, though some velocity-sensing meters can be fixed externally.

Even if instrumentation is available, the variability of flow conditions will be an additional field complication. At present, dual instrumentation to measure both closed and open flow channel is very expensive. A more economical option may be to retroactively modify flow lines to force closed channel conditions using gooseneck or trap systems (Bachmann 2007). This will only be feasible if there is local interest in retrofitting and funding to do so.

While instrument use will be constrained principally by cost, operational specifications are also important. Each instrument will function across a specific range of discharges and pipe diameters, specified by the manufacturer. Consult Dodge (2001) for an overview on closed conduit discharge instrumentation.

In all cases, security of equipment will be a concern. Any equipment openly installed over tubing or left aboveground will be vulnerable to theft and vandalism.

1.4.3.3 Hazen-Williams and Darcy-Weisbach equations

Much as Manning's equation can be used to estimate open channel flow, there are two equations that can be used to estimate discharges from full pipe flow (Driscoll 1986). The Hazen-Williams and Darcy-Weisbach equations are used for determining optimum pipe diameters and estimating frictional head loss in the design of pipe systems. With some limitations, they can be used to estimate mean velocity (and thus discharge) in an existing system under full pipe flow.

Solving the equations will require knowledge of pipeline geometry between two points, including pipe diameter, material, pipeline length, and the relative elevation difference between the points.

The solution is based on Bernoulli's theory of energy conservation (Driscoll 1986) between two points along a flow line:

$$\frac{1}{2g} v_1^2 + z_1 + \frac{p_1}{\rho g} = \frac{1}{2g} v_2^2 + z_2 + \frac{p_2}{\rho g} + h_f \quad (1.9)$$

v_1 = velocity at point A (m/s)
 v_2 = velocity at point B (m/s)
 g = acceleration of gravity (m/s²)
 z_1 = elevation at point A (m)
 z_2 = elevation at point B (m)
 p_1 = pressure at point A (N/m²)
 p_2 = pressure at point B (N/m²)
 ρ = density of the fluid (kg/m³)
 h_f = frictional head loss (m)

This method is valid for incompressible and steady flow. It makes the assumption that the fluid is of uniform temperature and density. Minor head losses (in meters) due to pipe fittings or valves may be calculated or assumed to be negligible.

If point A and point B are inlet and outlet points at atmospheric pressure, we can make the rough generalization that p_1 is equal to p_2 . If pipe diameter is constant, v_1 must be equivalent to v_2 due to the law of continuity.

These assumptions allow the equation to be simplified in terms of frictional head loss:

$$z_1 - z_2 = h_f \quad (1.10)$$

The Darcy-Weisbach or Hazen-Williams equation is then substituted into equation (1.9b). Hazen-Williams states:

$$h_f = \frac{v^{1.85} L}{k^{1.85} C^{1.85} R^{1.17}} \quad (1.11)$$

v = mean velocity (m/s)
 k = coefficient dependent on units (0.849 for metric system)
 C = roughness coefficient (unitless)
 R = hydraulic radius (cross-sectional area divided by wetted perimeter of flow) (m)

L= length of pipeline (m)

Darcy-Weisbach states:

$$h_f = f_d \frac{L}{D} \frac{v^2}{2g} \quad (1.12)$$

D = hydraulic diameter (in circular pipes, this equals internal diameter) (m)

g = acceleration due to gravity (m/s²)

f_d = Darcy friction factor (unitless; found from a Moody diagram or by solving the Colebrook equation)

Discharge rate can be found by isolating the mean velocity term on one side of the equation and multiplying that mean velocity by pipe area, as in equation 1.2.

If pipe diameters vary along significant lengths of pipeline, the assumption of equivalent velocities will not be valid. In this case, the frictional head loss along each segment can be considered additively:

$$\frac{v_1^2 - v_2^2}{2g} + z_1 - z_2 = h_{f1} + h_{f2} \quad (1.13)$$

The principle of mass conservation states that in an incompressible fluid, velocity will decrease with increasing conduit area (and vice versa). Equation (1.13) can be solved for V₁ by substituting a form of the continuity equation into V₂:

$$\frac{v_1 a_1}{a_2} = v_2 \quad (1.14)$$

1.4.3.3.1 Limitations

The advantages and disadvantages of these two energy loss equations have been examined widely in the literature. Darcy-Weisbach is a theoretical equation that is accurate over all ranges, including a friction factor that is dependent on pipe roughness, diameter, fluid viscosity and density, and turbulence (i.e. Reynolds number). In contrast, the Hazen-Williams formula was empirically derived over a particular range of conditions. Its users typically assume a constant roughness coefficient based on pipe material.

Liou (1998) argues that the assumption of a constant roughness coefficient for the Hazen-Williams equation is not valid outside of the conditions under which they were derived (especially pipe diameter and turbulence). As the Hazen-Williams equation does not explicitly account for many of the factors that influence friction, it often disagrees with the more accurate Darcy-Weisbach equation.

The disadvantage of the Darcy-Weisbach equation is that it can be cumbersome to use, requiring an iterative solution for the Darcy friction factor using a Moody diagram or the Colebrook-White equation. The equation and Moody diagram can be found in any fluid mechanics textbook, for example Chanson (2004). Hazen Williams may be used somewhat more accurately where there is less friction due to turbulence, i.e., in large diameter pipes with low flow velocities.

As with any equation, field conditions may vary significantly from the ideal or may not be known with certainty: older PVC pipes may be rougher than reported in the literature; exact water

temperature may not be known; for handheld GPS surveys, pipeline length or point altitudes may have error upwards of ± 10 m. Considering these uncertainties and calculating discharge using the range of possible values will help to quantify the uncertainty in field data.

1.4.4 Tracer Methodologies

Tracer methodologies are typically employed where channels are irregular and flow velocity or cross-sectional area is difficult to measure. They may be used in both closed and open channel systems, though the technique originally evolved in mountainous catchments that were not used as a direct drinking water source (e.g., Day 1977).

Chemical and colorimetric tracers are commonly used, but where spring water sources will be used as a potable drinking water source, such tracers may not be appropriate. It is crucial that chosen tracers not be objectionable to consumers in taste, odor, or color, and that they be safe for human consumption.

Salt or heat are the most widely available tracers and may be most practical in lower-income areas in small or medium-sized springs (Dodge 2001). Either velocity or concentration of the tracer will need to be measured, requiring moderately advanced equipment such as temperature or conductivity probes. Such equipment is likely to represent a significant investment in lower-income areas (\$100-200), and the technique requires a high degree of user training. For concentration measurements, a constant injection rate will also need to be achieved. This is typically accomplished using automated equipment, which is unlikely to be available.

If a safe dye is available and cross-sectional area can be measured, flow can be roughly estimated by timing the travel of the dye cloud from one point to another and multiplying the velocity (length of travel over travel time) by cross-sectional area. For more information, see Dodge (2001).

1.5 MEASUREMENT ERROR

In spring discharge measurement, as with any measurement, it is important to be aware of sources of error. The amount of acceptable error will depend on the accuracy required to meet the goals of discharge monitoring. It may not be possible to achieve an ideal degree of accuracy in the field. Nevertheless, it is important to identify sources of measurement uncertainty, quantify them where possible, and reduce them as much as possible.

Especially in cultures with more indirect styles of communication, strong communication between team members is important for reducing avoidable errors introduced by user confusion. There are three main types of error frequently cited: systemic, random, and spurious errors (Dodge 2001).

Systemic errors are constant and cause the measurement to vary from the actual value in a consistent direction. They are inherent in the measuring system, either in the equipment used for measuring, or the entity being measured. An example would be a bucket that is incorrectly calibrated or a constant leak upstream from discharge measurement. Systemic sources of error cannot be identified over repeated measurement and can be difficult to identify in the field. For this reason it is advisable to employ multiple measurement techniques whenever possible to check for systemic errors.

Random error is also inherent in the measuring system, but varies over the timescale of measurement. An example would be slight and unavoidable variations in the speed with which someone operates a stopwatch. The influence of random error can be reduced by averaging measurements over several repetitions. For that reason, measurements should always be repeated at least three times, and more, if possible. It is important to take many measurements if random measurement error is suspected to be larger than the required accuracy.

Spurious errors are mistakes caused by user carelessness, incompetence, or random disruptions. An example would be a technician who reads a height incorrectly because he is unfamiliar with the staff gage or who drops her stopwatch after a bee sting. This error will be evident if the source is eliminated between measurements and such trials should be thrown out and repeated.

1.6 CONCLUSION

Springs are an important water source worldwide as they are both relatively protected and easily accessible at the surface. With global temperatures rising and fresh water demand increasing worldwide, the informed management of springs is all the more pressing. Discharge monitoring is an important tool for spring resource management. Knowledge of seasonal variation in discharge is necessary for basic water conservation from season-to-season. It also provides an important signal of the response of the local catchment and aquifer to particular climactic inputs, as well as facilitating the prediction of future responses under varying climate and land use scenarios.

Discharge monitoring can be relatively low-cost and easy to implement compared to water chemistry monitoring. Therefore, discharge monitoring may be an important first step to inform water management in low-resource settings. The selected monitoring methodology must be technically feasible in terms of the magnitude of discharge, spring configuration (captured or uncaptured), and spring hydraulics (closed or open channel flow). Selection of the most appropriate methodology will depend equally on available social and economic resources. Ultimately, the success of long-term spring monitoring in low-resource areas will depend both on technical considerations (spring hydraulics) and the availability of economic and social resources to implement monitoring in that particular context.

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2 CASE STUDY OF SPRING MONITORING CONCEPCIÓN CHIQUIRICHAPA, GUATEMALA

2.1 BACKGROUND AND FIELD AREA

This study was undertaken during my two-year Peace Corps assignment as a Sustainable Community Tourism Facilitator in the municipality of Concepción Chiquirichapa, Guatemala. The work arose in collaboration with my assigned counterpart agency, the municipality's Department of Protected Areas and Environment. The following section summarizes the geographical characteristics of the field area and motivation for the study.

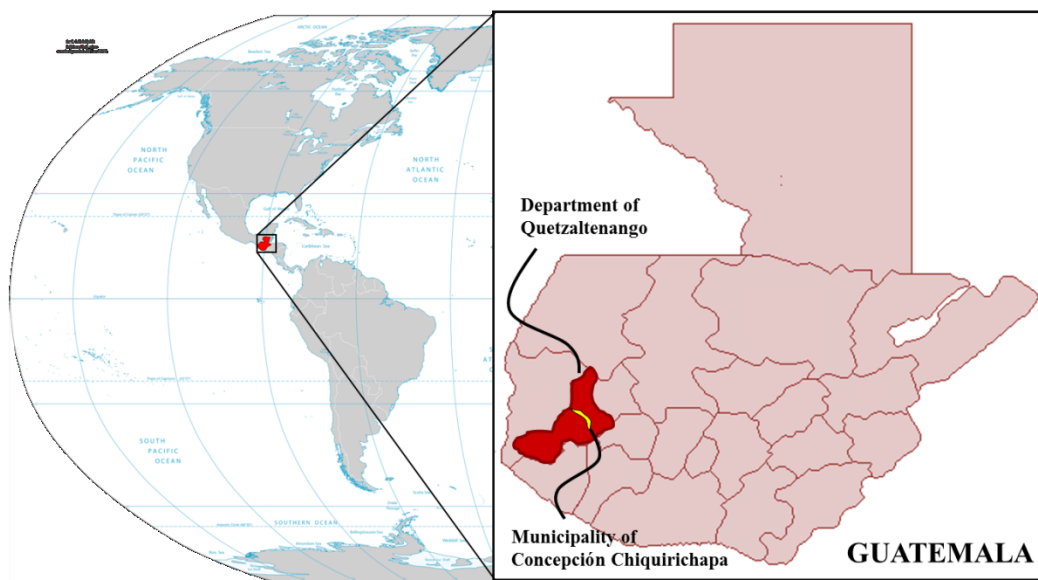


Figure 2.1. Regional map of field site (adapted from Wikipedia Commons 2013a and 2013b).

2.1.1 Physical Geography and Climate

Concepción Chiquirichapa (14.8500° N, 91.6167° W) is a municipality in the mountainous, western highlands of Guatemala, Central America. It encompasses an area of 48 square kilometers, with an average altitude of 2,600 meters above sea level (masl). The municipality borders the northern edge of the Sierra Madre de Chiapas, with quaternary volcanic ridges rimming the municipality to the west and south.

Diurnal fluctuations in air temperature are greater than seasonal variations in the region, with the municipality experiencing average highs between 25 to 27 °C and night-time lows from 3 to 5 °C, with occasional sub-zero evening temperatures in January and February. The municipality has a distinct dry season from November to March and wet season from May to October. The nearest weather station, Labor Ovalle, lies at 14 kilometers distant and an elevation of 2400 masl. The station receives 0.7 to 1 meters of rain per year on average (INSIVUMEH 2012).

The region is prone to tropical cyclones during the wet season that typically cause landslides, flooding, and significant damage to infrastructure. One such tropical cyclone, Tropical Depression 12E, occurred during the study period. The storm occurred from October 12-13, 2011, during

which time total precipitation of 12.7 cm was recorded at Labor Ovalle (INSIVUMEH 2012). For comparison, 23.3 cm of rain was recorded at Labor Ovalle during Tropical Storm Agatha (May 29-May 30, 2010), which was one of the most extreme precipitation events to occur in Guatemala since records have been maintained (INSIVUMEH 2012).

The principal land covers in the municipality are farm land (40%) and forest (60%) (Municipality of Concepción Chiquirichapa 2010). The majority of forested land has been disturbed historically. Natural forest type varies with elevation from subtropical deciduous/broadleaf to mixed deciduous/evergreen (Helvetas ProBosques 2008).

The local geology is composed of thick quaternary volcanic deposits principally comprising pumice, ash falls, and andesitic lava flows. The municipality's southern border is formed by Volcán Siete Orejas, whose last major eruptive period was constrained by Rose et al. (1999) to have occurred between 158,000 and 84,000 years before present.

2.1.2 Hydrology

Most of the territory is located in the Samalá River Basin, while the minor portion of municipal territory in the caldera of Siete Orejas feeds the Ocosito River Basin. Both watersheds drain into the Pacific Ocean.

The municipality has several smaller rivers originating on the surrounding mountainous slopes; most are sub-tributaries to the Samalá River. These are highly contaminated with plastic trash and other solid wastes, as many riverbeds are used for trash disposal.

There are numerous water springs on municipal lands, found at various elevations on the slopes of quaternary volcanoes to the south (Siete Orejas) and west (Lacandon). The majority are cold-temperature, with one hot spring in the crater of Siete Orejas at an elevation of 2100 m.

Table 2.1. Water springs in the municipality. Elevation data were derived from a digital elevation model (IGN 2006) and coordinates obtained from Helvetas ProBosques (2008) () and field work using handheld GPS (§).*

| <u>Location</u> | <u>Number of Springs</u> | <u>Elevation (masl)</u> |
|---|---------------------------------|--------------------------------|
| Xecacaix | 1 | 2764 m * |
| Xecampana (Toj Coral) | 5 | 2730 - 2760 m § |
| Aguas Palomas | 5 | 2818 - 2828 m § |
| Toj Isb'en / Toj Baq'man | 1 | 2980 m * |
| Tuilcanabaj and Duraznales 1&2 (Cacique Dormido) | 3 | 3120 - 3140 m * |
| Aguas Calientes | 1 | 2100 m * |

2.1.3 Population and Water Supply

According to figures released in the municipality's most recent diagnostic (Municipality of Concepción Chiquirichapa 2010), the municipality has 23,000 inhabitants, 98% of whom identify as indigenous Maya-Mam. Approximately 6,000 inhabitants live in the urban center, while the other 17,000 are spread throughout 18 other smaller communities.

Due to contamination of surface water, the urban center's household water supply comes almost exclusively from spring sources originating in forested catchment areas. This water is distributed via a centralized gravity-fed system. According to SEGEPLAN (2011), 99.5% of urban households have running water installed, although shortages are common from April to June.

Based on participant observation, the majority of complaints from urban residents about water supply relate to these shortages, though severity varies in different sectors of the urban center, and there is limited data regarding their frequency and spatial distribution. Some households resort to makeshift rainwater catchment at the beginning of the rainy season.

Tests conducted by the local health center reveal microbial contamination in some water springs, and the municipality shock chlorinates the system on occasion. Regardless, it is a secondary concern for many residents as the majority of them boil municipal water before consumption.

In addition to household supply, some water demand arises from agriculture. The majority of the population (approximately 90% of adult males) dedicate themselves to agriculture, with principal crops including potatoes, broccoli, and other hardy vegetables (Municipality of Concepción Chiquirichapa 2010).

Groundwater sources for the urban center include two high discharge springs, one tunnel aqueduct intersecting the water table, and 5-6 low-to-mid-volume water springs (see Table 2.2).

Table 2.2. Table of municipal water sources for the urban center with approximate discharge magnitudes in liters per second (l/s).

| Name/ Location | Magnitude | Monitored in this study? |
|--------------------------------|------------------------|--|
| Toj Coral #1 "Big" - Xecampana | Large (> 10 l/s) | Y – via a release valve |
| Toj Coral #2 | Small (< 1 l/s) | Y – simple junction box |
| Toj Coral #3 | Small | N – tubing broken during Tropical Storm Agatha (May 2010) |
| Toj Coral Tunnel - Xecampana | Small | Y – tubing could be separated |
| Aguas Palomas #1 | Medium (1 – 10 l/s) | Y – simple junction box |
| Aguas Palomas #2 | Medium | Y – simple junction box |
| Aguas Palomas #3 | Small | Y – simple junction box |
| Aguas Palomas #4 | Medium | Y – simple junction box |
| Las Barrancas | Large | N – very remote; tubing frequently broken; distribution system not conducive to measurement without significant modification |

The two municipal water sources considered in this study are located in forests outside of the municipal seat/urban center of Concepción Chiquirichapa (Figure 2.2): Aguas Palomas, located near the villages of Telená/Tzicol (2.5 km from center), and Xecampana, located outside of the village of Toj Coral (2 km from center).

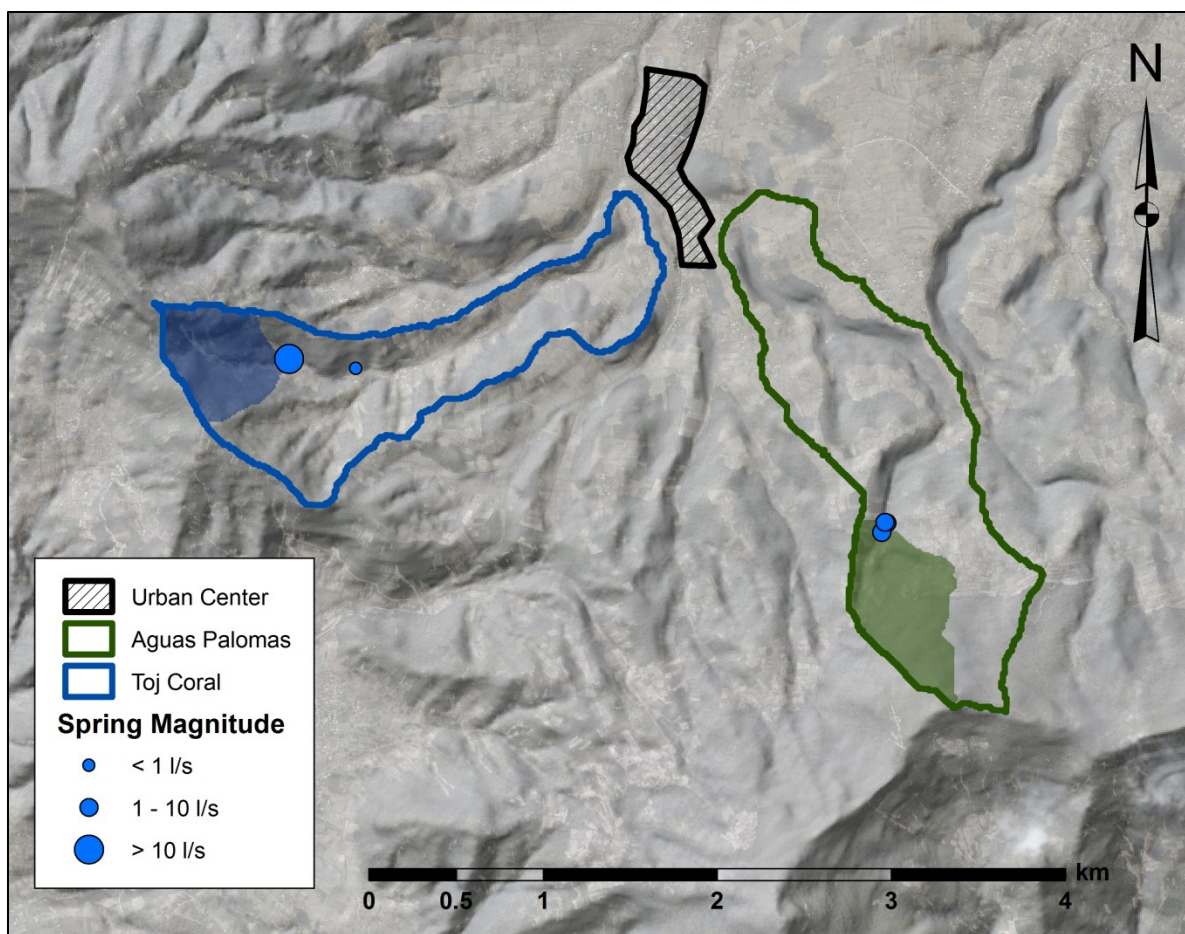


Figure 2.2. Map of two subwatersheds (solid outline) and delineated water spring catchment areas (hashing). Base map: MAGA (2006) provided by SEGEPLAN/SINIT/IDE.

The author identified at least six other spring sources in these same sub-catchments on municipal lands, even next to municipal springs. In practice, however, these belong to smaller communities to whom the municipality cedes sole use. Municipal employees saw the monitoring of these sources as infeasible, citing tension between the municipality and certain local groups over land tenure, with one municipal employee retreating from Aguas Palomas by forcible threat on one occasion.

Spring-discharge monitoring was proposed to two communities via a local health organization, but community members were not interested, citing concerns over the use of the information.

2.1.4 Research Impetus

Employees of the municipality's Department of Protected Areas and Environment (DPAE) and Municipal Plumbing Office are interested in quantifying spring resources in order to better manage them. One specific concern is the improvement of water service to some 6,000 users in the "urban center" of the municipality, who experience frequent water shortages in the dry season.

Municipal water sources are designated to be monitored monthly under DPAE's Annual Operating Plan, though other priorities, limited human resources, and lack of administrative organization have made monitoring sporadic in the past.

The initial objectives of this research were:

(1) Implement semi-continuous discharge monitoring in two municipal water springs in Aguas Palomas and Toj Coral.

(2) Utilize discharge measurements in order to characterize these two aquifers using time series and water balance analyses.

While the quantity and quality of data collected did not support these initial goals, this research experience highlights the potential of water spring discharge monitoring for characterizing small mountainous aquifers, as well as common challenges in implementation of spring discharge monitoring.

2.2 METHODS

Due to limited human resources, it was not possible to measure flow in the municipal water sources on a daily or even weekly basis. From this restriction the idea arose to measure flow on a semi-continuous basis indirectly via water-pressure loggers. The intention was that monthly manual flow measurements could be plotted against their corresponding water level measurements to obtain a stage-discharge curve, as in conventional stream gaging (Buchanan and Somers 1969).

Field measurements of spring discharge were taken monthly using volumetric methods, and water-level height in two of the spring boxes was measured using water-pressure loggers. After data collection, I attempted to filter the data for atmospheric pressure disturbances. Data were then analyzed to identify whether a consistent relationship existed between water level height and spring discharge (measured manually).

2.2.1 Field Measurements



Figure 2.3. Junction box at Aguas Palomas. Note black chord from which water-pressure logger was suspended.

Manual spring-flow measurements were made on a monthly basis when possible, at the same time water-pressure logger measurements were retrieved. These measurements were fairly straightforward at Aguas Palomas, where flow from four separate springs was measured in a junction box using a calibrated bucket and stopwatch. The final discharge is reported as the average of three or more trials.

Measurement in the large Toj Coral #1 spring was more complicated. Flow in this spring seeps from a five-meter long crack covered by a large spring box structure. This flow is directed along a short canal into a smaller spring box with a four-inch-diameter outlet pipe.



Figure 2.4. Inside of Toj Coral spring box where water-pressure logger was installed prior to overflow tube modification. Spring flow direction out of rock wall indicated with blue arrow.



Figure 2.5. Left: Springbox at large Toj Coral spring (#1). Right: Measuring discharge at the downstream valve installed in a creek bed approximating 500 m downhill of the spring box.

Direct measurement in Toj Coral was possible only at a valve installed for that purpose beside a creek bed downstream, though it was later understood that the valve likely only diverts a side stream of the main flow into the creek bed. In addition to that uncertainty, high flow rates made container/stopwatch measurement unreliable and even impossible at higher discharges due to water turbulence. Water-discharge plume dimensions were measured on several occasions in order to estimate discharge using the Purdue methodology (Brown 2006; Hohn 2002).

Prior to May 27, 2011, the water within the spring box was diverted through two outflow tubes, one of which had been modified to accommodate increased discharge after Hurricane Stan in 2005. The vertical tube was originally designed for overflow, and there was no place along the line where flow from the overflow tube could be measured. The overflow tube was lengthened to 31 cm, after which all flow was forced through the primary horizontal outlet (see Figure 2.6). Shortly after, the water level began to oscillate with a cyclical pattern of “chugging and filling” (see Figure 2.6).

Monthly manual measurements were also made at a smaller municipal spring and the municipal water tunnel in Toj Coral using calibrated bucket and stopwatch. Due to low discharge rates, these measurements were straightforward. The distribution piping of the small spring was broken during Tropical Depression 12E in October 2011.



Figure 2.6. Images of the adjustment made to the overflow tube in the largest Toj Coral spring (#1). Note green chord from which water-pressure logger is suspended.

Two Levellogger Gold 3001 M5 data loggers (Solinst Canada Ltd., Georgetown, Ontario) were installed for the purpose of collecting measurements of water-column height above the sensor and temperature. The loggers can store up to 40,000 temperature/water-level readings and have a calibrated range of 5 m water depth. The sensor is unvented, measuring combined atmospheric pressure and water pressure, with a manufacturer-specified accuracy of ± 0.3 cm. Sorenson and Butcher (2011) determine that field accuracy can vary as much as ± 1 cm in similar sensors, though their study considers water-level changes on the order of decimeters. They determine that accuracy also varies based on the quality of atmospheric compensation.

One data logger was installed in the largest spring box in Toj Coral (“Toj Coral #1” – see Figure 2.6). It was deployed from May 2011-March 2012 and discontinuously recorded 10 months of data. A second data logger was installed in the junction box that combines the flow of the four separate Aguas Palomas springs (“Aguas Palomas #1-4”) from June 2011-March 2012, which discontinuously recorded 6 months of data. See Figure 2.3. for an image of Aguas Palomas installation.

Data was initially recorded at a 15-minute resolution and subsequently at a 1-minute resolution on both data loggers, with the disadvantage that the instrument memory filled every 27 days and did not provide a continuous record of water-level height when scheduled visits were delayed. In Toj Coral, water-level height was recorded at the same time data were retrieved. Water-level measurements were not made in Aguas Palomas.

Logger measurements are missing for longer time periods during which the logger filled with data and it could not be retrieved from the spring, for example due to Tropical Depression 12E in October and extended municipal vacations in December. After December, recording resolution was reduced to 5 minutes in both spring boxes. The data logger was stolen from Aguas Palomas in early March, therefore data are missing in Aguas Palomas after the last download that preceded the theft.

2.2.2 Temperature and Precipitation

Daily weather data were obtained from the National Institute of Seismology, Volcanology, Meteorology, and Hydrology (INSIVUMEH) for Labor Ovalle station outside of Quetzaltenango (coordinates: 14°52'16"N 91°30'53"W, at an altitude of approximately 2400 meters above sea level). Where referenced, this data is cited as INSIVUMEH (2012). The Labor Ovalle station is approximately 14 km from Toj Coral and 11 km from Aguas Palomas, which are at 2750 masl and 2800 masl, respectively.

2.2.3 Levellogger Data Processing

The Solinst Levellogger 3001 measures absolute pressure (atmospheric pressure plus water pressure); subsequently, there is significant atmospheric noise within the data, including diurnal and semidiurnal atmospheric tides¹ and fluctuations based on regional weather systems (see Figure 2.7). Both sources of noise are significant for the purpose of logging water height: diurnal variations cause an apparent fluctuation of 2-3 cm in water level, while extreme regional weather systems such as tropical depressions can cause an apparent fluctuation as great as 7 cm. In longer-term studies this may be a significant source of error, as the instrument has a maximum accuracy of ± 0.3 cm under controlled conditions. Similar instruments have shown a minimum field accuracy of ± 1 cm, with typical field precision of ± 0.15 cm (Sorenson and Butcher 2011).

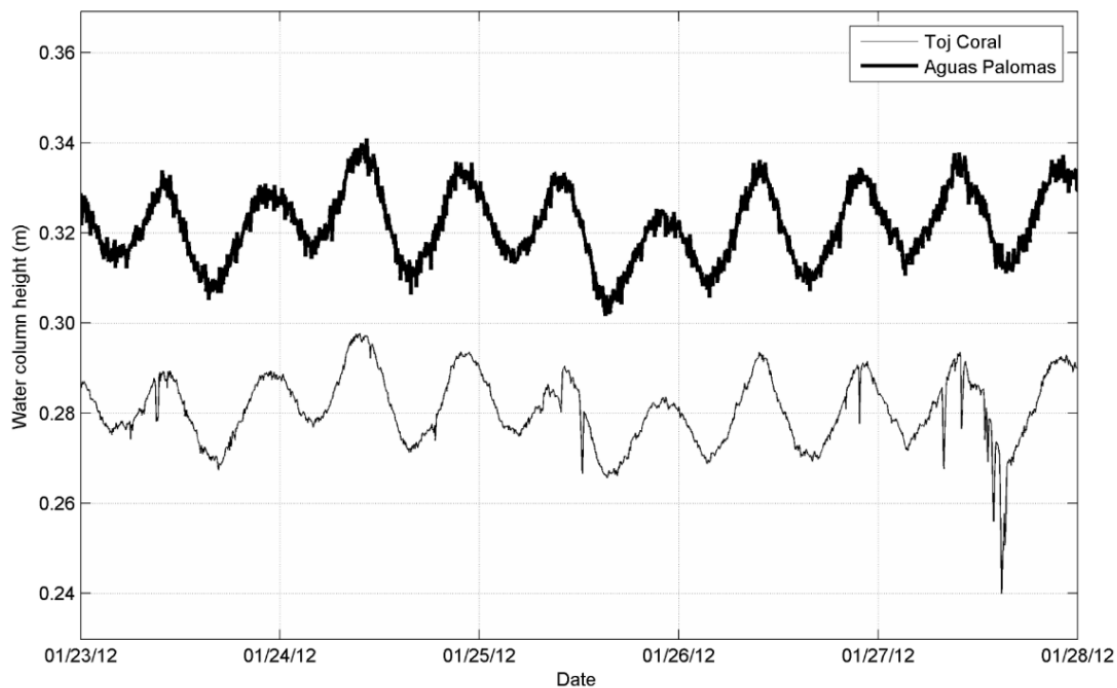


Figure 2.7. Strong correlation in the water-pressure logger data from both Toj Coral and Aguas Palomas stations reflects cyclical variation in atmospheric pressure. Diurnal atmospheric pressure variation is a well-documented phenomenon (e.g., Lindzen 1979).

¹ Atmospheric tides are periodic fluctuations in the atmosphere related principally to daily cycles of solar heating in the lower and middle atmosphere. For this reason they may also be called “thermal tides”, though a small component of the tides is caused by lunar and solar gravity (Lindzen 1979).

Prominent atmospheric signals with periods of 12 and 24 hours were evident in the time domain. Other minor spectral peaks are reported in the literature for $T=8$ hrs, 6 hrs, 4.8 hrs, 4 hrs (Kamata et al. 2002) but filtering for these four peaks had little effect, reducing the variation in water level less than 2 mm on average. Therefore, data were filtered only for a range around the most prominent frequencies of $2.31(10)^{-5}$ Hz ($T=12$ hrs) and $1.157(10)^{-5}$ Hz ($T=24$ hrs). Figure 2.8 shows the effect of filtering for these six frequencies. Data were zero-phase filtered using 2nd order Butterworth bandstop filters constructed in MATLAB.

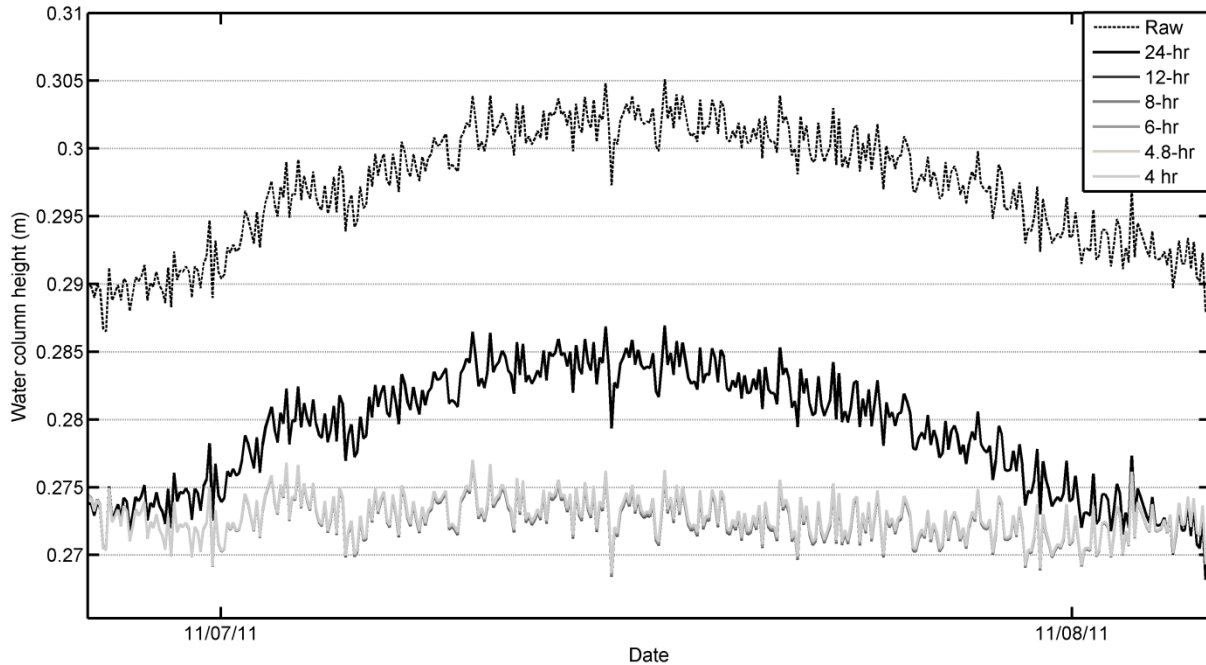


Figure 2.8. Filtering the data for periods of 12 and 24 hours significantly reduces atmospheric noise. Other atmospheric frequencies do not contribute significantly to the raw signal.

After filtering, data were corrected for regional atmospheric pressure variations using average daily barometric pressure readings from the INSIVUMEH weather station at Labor Ovalle at 14 km distant from the municipality. The daily barometric pressure readings were converted from millimeters of mercury to water column height in meters. The average daily barometric pressure recording in meters of water height was assigned to the time of noon on each day and a dataset at the time interval of the level recording (15 minutes, 1 minute or 5 minutes) was created by interpolating linearly between each daily average at the resolution of the record. This approximate barometric pressure record was then subtracted from the level dataset.

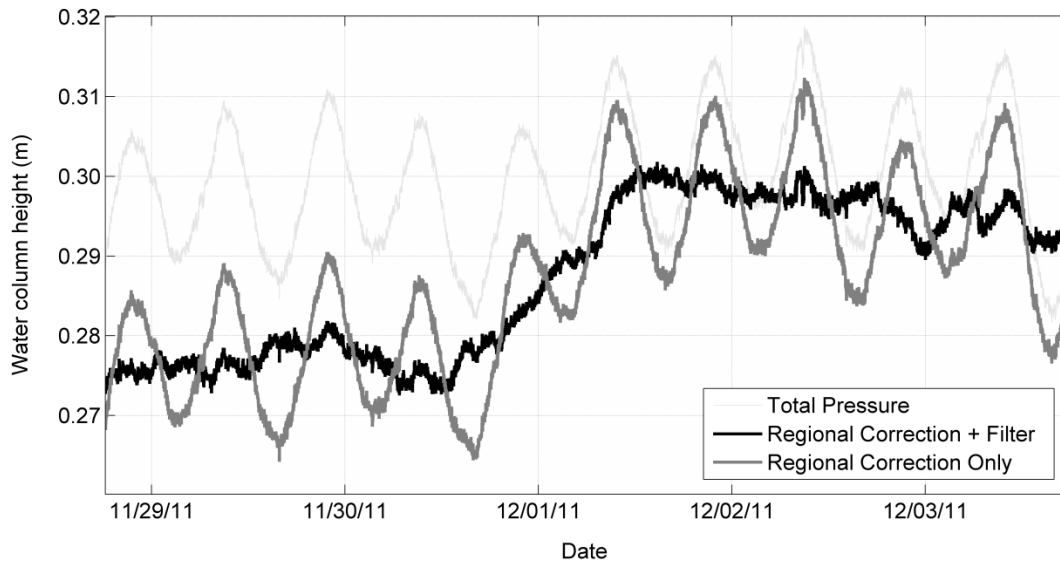


Figure 2.9. Raw data in light gray contrasted with data corrected for regional atmospheric variation in gray. Data corrected for regional variation and then filtered for diurnal and semidiurnal atmospheric signals of period 12 hrs and 24 hrs are shown in black.

Prior to atmospheric pressure filtering, the data were edited to remove instances when the water-pressure logger was removed for data downloading, clearly identified from field notes and from spikes in both pressure/temperature in data plots.

In the Toj Coral data, physical measurements of water height and spring box geometry were taken in order to register the data to an actual water level height. This method is limited, as the manual height measurements were almost always made at the beginning of recordings, where filtering is least effective and uncertainty in the atmospheric correction is around ± 1 cm. Rather than a precise registration of the data to these manual measurements, the average data baseline was registered to the known baseline of the top of the outflow tube.

In the Aguas Palomas data there is evidence of major undocumented disruptions. These most likely relate to sudden water level drops when municipal plumbers drained the box for maintenance. There is also evidence of offsets in the Aguas Palomas data that indicate the chord suspending the water-pressure logger was not always replaced in the same way following planned visits, leaving the water-pressure logger recording at a height in the water column higher or lower than its original datum.

Where there is a continuous record, these offsets were corrected to a common datum prior to filtering. Potential offsets occurring after large gaps in data could not be identified definitively since there was no intermediate record to exclude the scenario of gradual water level change.

2.3 RESULTS AND DISCUSSION

2.3.1 Manual Flow Measurements

The higher-magnitude springs (Toj Coral #1, Aguas Palomas #2 and #3) showed a definite increase in flow following the extreme precipitation of Tropical Depression 12E (see Figure 2.10), though the data points from Toj Coral #1 offer only a qualitative comparison of discharge as only an unknown portion of the flow stream was captured.

In the smaller springs and one tunnel, flow was relatively constant throughout the season, with a slight increase in discharge after Tropical Depression 12E. There is no post-storm record at Toj Coral spring #2 as the tubing from that spring was broken in the storm. These discrete data points taken at different times of day are insufficient to draw rigorous comparisons between the two aquifers, or even between the different springs.

Water temperature measured by the data logger was constant within a 0.1°C range of 12.4°C in Toj Coral and 11.7 °C in Aguas Palomas throughout the entire record of the data loggers. Water tested sporadically at Aguas Palomas and Toj Coral from May 2011 to March 2012 ranged in pH from 6.38 - 6.87 with no clear spatial or temporal pattern. These values are likely low: the pH meter used was un-calibrated and later found to vary approximately -0.3 pH units from standard solutions.

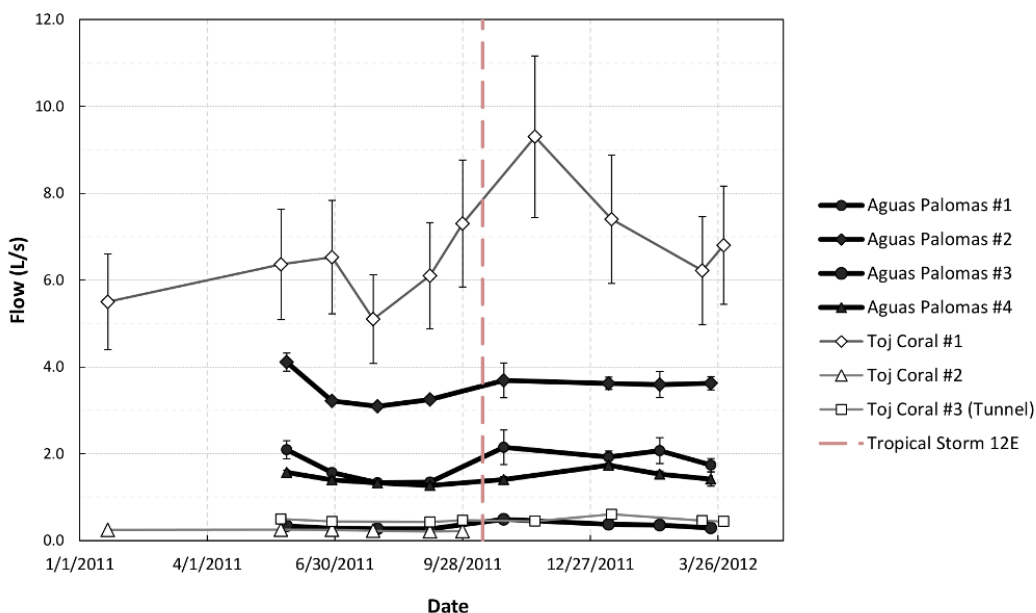


Figure 2.10. Discrete spring measurements at two Toj Coral springs, one Toj Coral tunnel, and four Aguas Palomas springs. Dashed line represents Tropical Depression 12E (October 12-13, 2011). Toj Coral #1 data points represent discharge measured from a side stream of the main flow. Error bars represent measurement uncertainty, specifically the coefficient of variation (ratio of standard deviation to mean) computed for all measurement trials. Measurement uncertainty was high in Toj Coral #1, where flow was often too high to measure accurately using the volume-time method.

2.3.2 Water Level Measurements

2.3.2.1.1 *Uncorrected Total Pressure Record*

The uncorrected water levels measured by the water pressure loggers are composed of two signals: atmospheric pressure and water column pressure (height). In both datasets, diurnal and semi-diurnal atmospheric tides introduce an apparent water column height variation of 2-3.5 cm, while regional weather systems introduce upwards of 7 cm of apparent variation. Human disruption to the data logger level also introduces apparent variations in water level (see Figure 2.11).

The atmospheric pressure signal is the most significant source of noise in the Aguas Palomas data. Filtering the dataset tightens the apparent spread in water column height by 40-70%. In Toj Coral from late May to mid-October 2011 the hydraulics of the distribution system introduced more noise than atmospheric pressure fluctuations. Filtering for atmospheric pressure variation only tightens the spread in apparent water column heights during these months by 10%.

The atmospheric correction is not very accurate: ripples upward of 2 cm in amplitude are evident at the beginning and ends of the filtered recordings, introducing seven times more uncertainty than the maximum instrumental accuracy (2.5 mm).

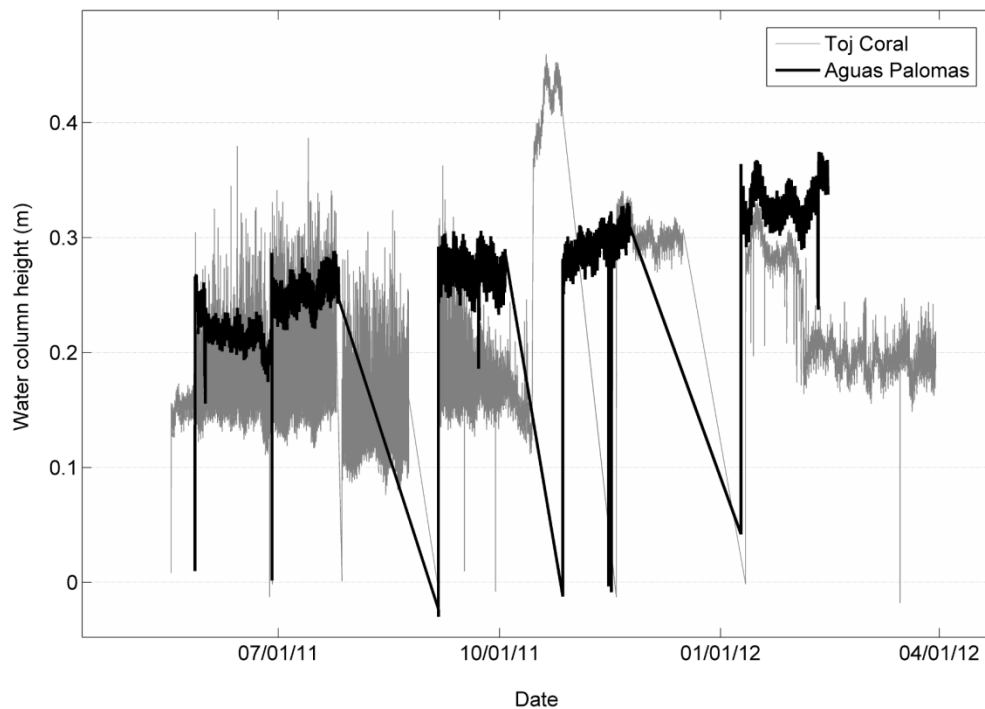


Figure 2.11. Time series of all uncorrected pressure levels (meters) recorded by the data logger. These levels are normalized for baseline atmospheric pressure, though not for daily or regional atmospheric pressure variations.

2.3.2.1.2 *Toj Coral Water Level Record*

In Toj Coral, the atmospherically corrected water level record is adequate for discerning general trends in water column height in the spring box as system hydraulics and spring discharge change.

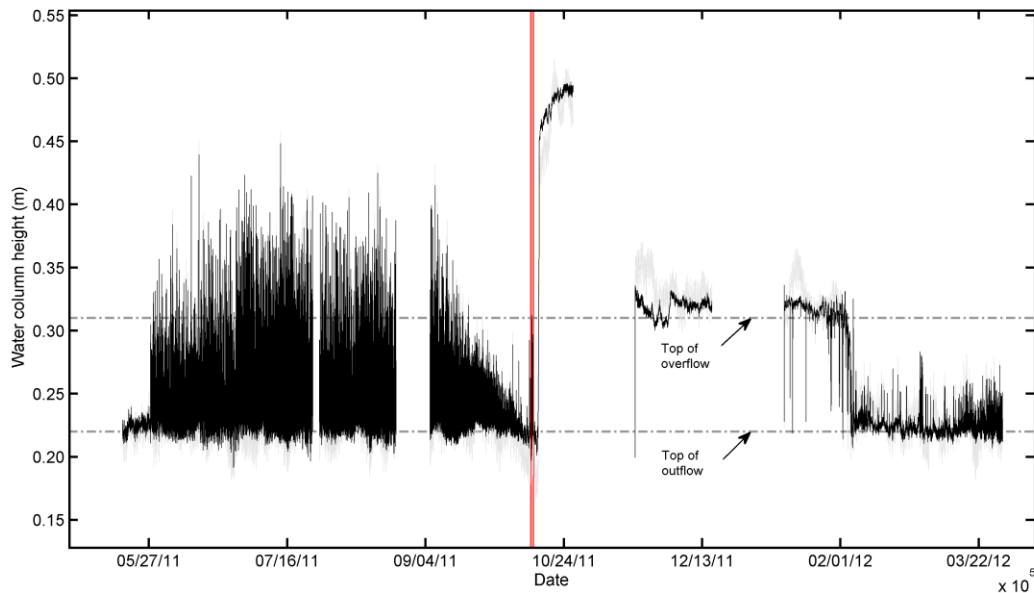


Figure 2.12. Time series of atmospheric correction of Toj Coral data (black), with data registered to average baseline. Raw data is in gray. Tropical Depression 12E is marked by a pink vertical line.

When monitoring began in May 2011, the system had a secondary outlet that was installed to accommodate increased discharge after Hurricane Stan in 2005. There was no place where this overflow could be quantified. Prior to May 27, the overflow tube was at the level of the top of the outflow tube and water was flowing out of both. The 4" pipe from the primary outflow travelled past a creek bed where a valve was installed to divert flow from a 2" pipe in order to measure it volumetrically. The overflow tube was extended on May 27 with the intention of forcing all flow through the main 4" outflow pipe down to the creek bed valve, although it was later understood that this pipe most likely was only carrying a side stream of the main flow.

When overflow was eliminated, the spring box immediately began cycles of slow filling, where water rose between 2-10 cm above the top of the outflow pipe, and fast "chugging", where the water seemed to be pulled into the pipe and water level was just below the level of the pipe, allowing air to enter the pipe. See Figure 2.13 for photographs of this process and Figure 2.15 for the corresponding data logger records.

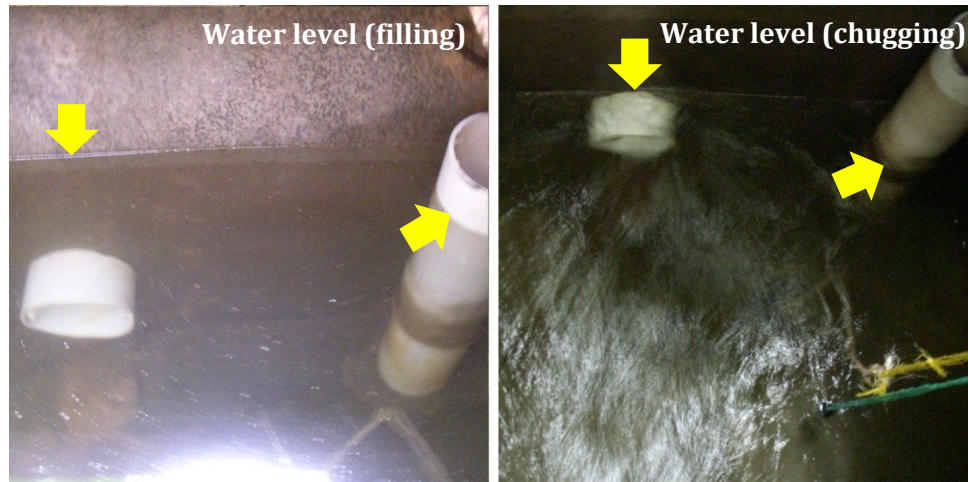


Figure 2.13. Images of different stages of cyclical filling and emptying: still filling (left) and fast chugging (right). Water level indicated with yellow arrows.

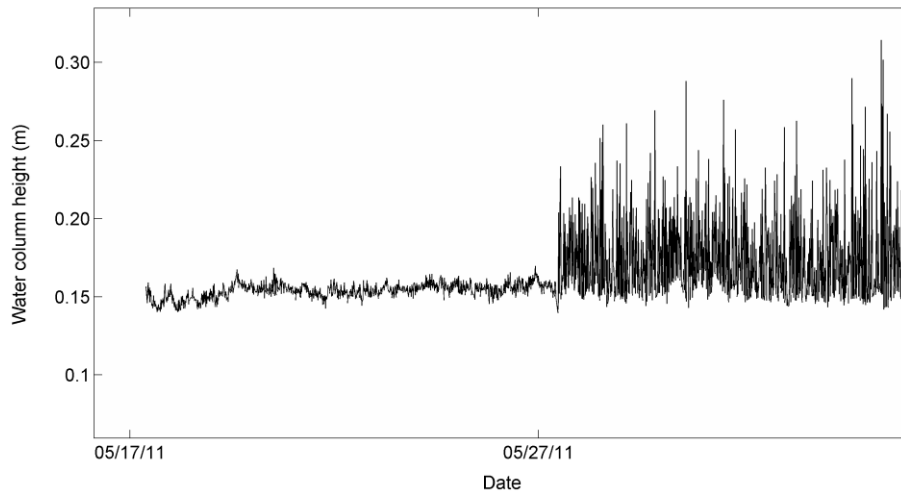


Figure 2.14. Data was collected with overflow from May 17-27. After May 27, overflow was eliminated in the system and the cyclical filling began.

From May 27 to October 14, the water level was constantly rising and lowering above the top of the outflow tube (see Figure 2.15). Example of cyclical filling process on a daily scale from 8 AM on July 9 to 5 AM on July 10.). Recorded water column height varies as much as 25 cm (± 1 cm) above this baseline, though the majority of peaks are just 2-10 cm (± 1 cm) above the baseline. These cycles have irregular periods, varying from 3-45 minutes. The shorter peaks (< 5 cm) generally correspond with periods less than 15 minutes. Neither larger peaks (> 9 cm above top of outflow tube) nor shorter peaks (2-9 cm above top of outflow tube) occur more frequently at a particular time of day (see Figure 2.16).

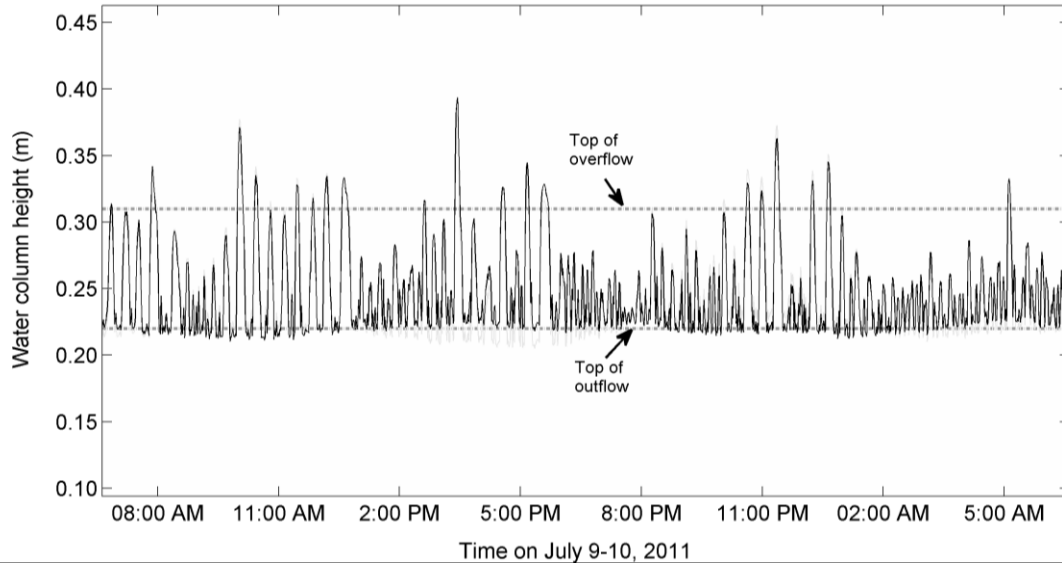


Figure 2.15. Example of cyclical filling process on a daily scale from 8 AM on July 9 to 5 AM on July 10.

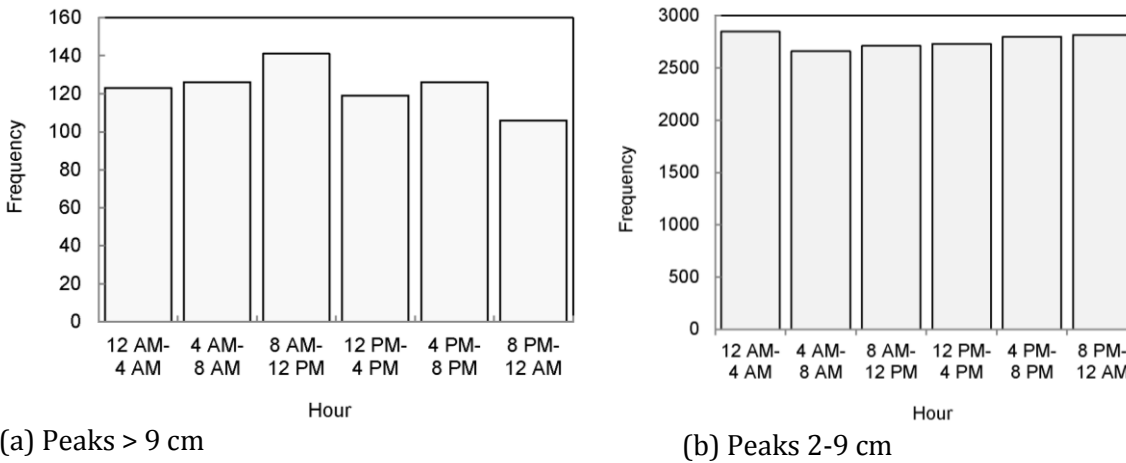


Figure 2.16. Histograms of the time distribution of peaks greater than 2 cm above the top of the outflow tube, showing that peaks are almost equally distributed in time.

Although water height within the spring box was changing cyclically, the average water column height is fairly constant from May 27 to mid-September. Between mid-September and October 12, 2011, the average water column height decreases as larger variations in water column height are less frequent and less extreme, with maximum variations less than 8 cm (± 1 cm).

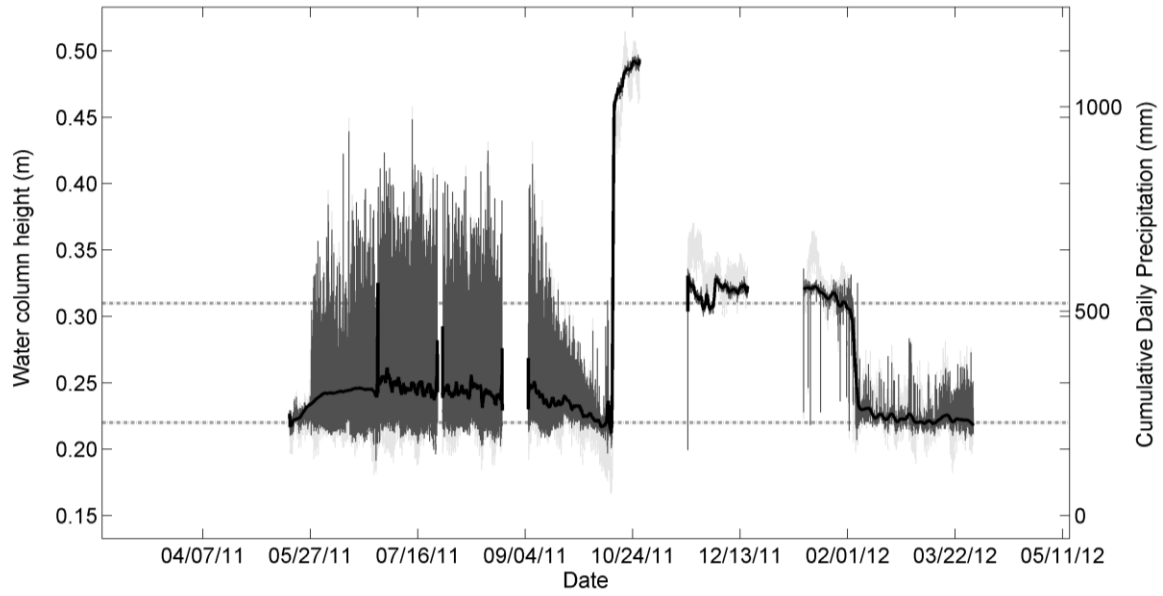


Figure 2.17. Plot of average water levels in Toj Coral (moving average in black, interval=20 hours). Actual water levels (atmospherically corrected) are in dark gray, raw data in light gray.

The time series marks three large spikes on October 12-13, 2011 when Tropical Depression 12E hit Guatemala. The first and second both occur over three hours, and the third over 41 minutes (see Figure 2.18). It is unknown whether these spikes represent spring discharge or direct infiltration of precipitation into the spring box, though the spring box was buried by a small landslide at some point between October 12 – 16. Two days after Tropical Depression 12E, the largest spike in water column height of the entire record occurs, with water level rising up to 50 cm above the bottom of the spring box. This approximate level is maintained at least until October 27.

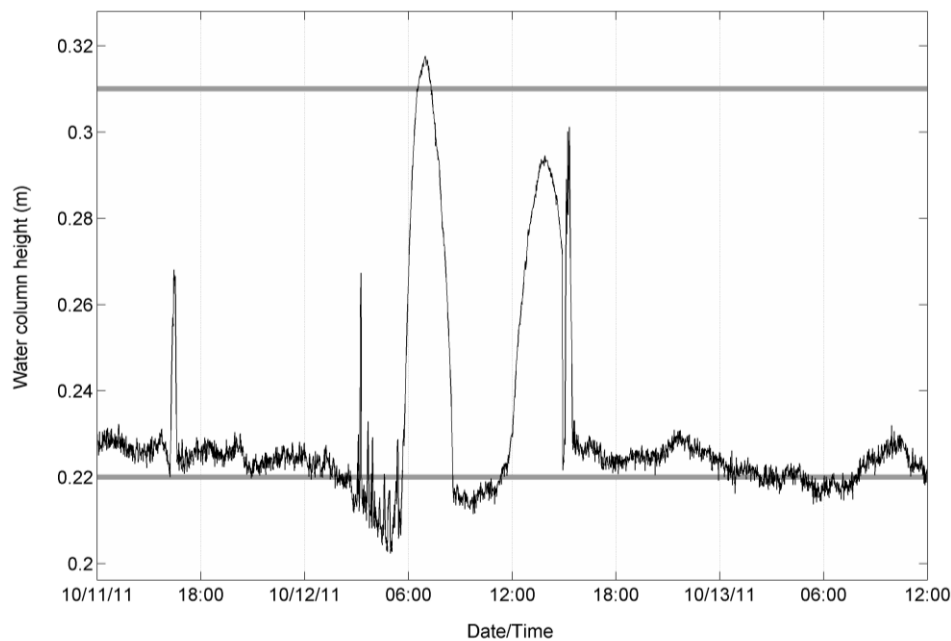


Figure 2.18. Peaks in water level height on October 12 in Toj Coral spring box.

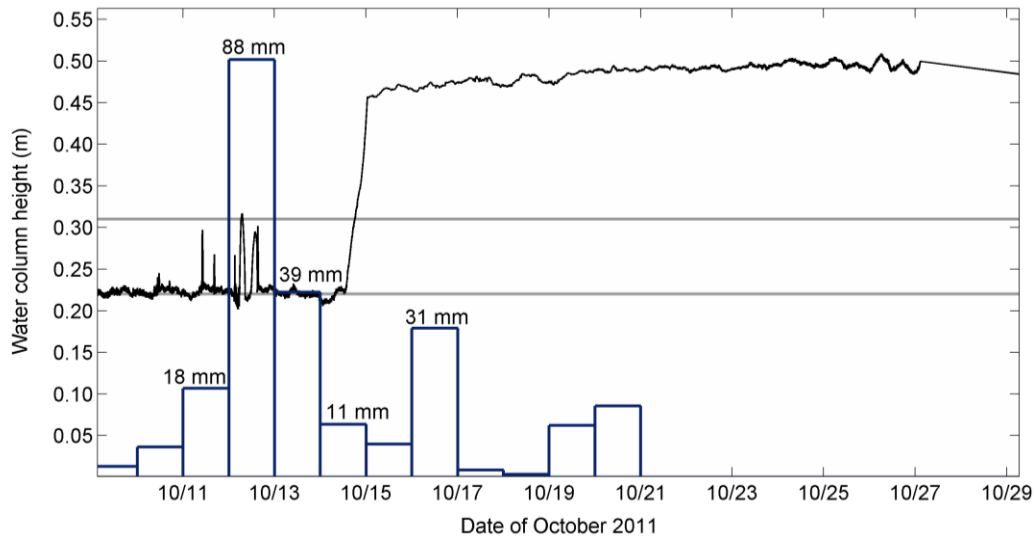


Figure 2.19. Water level height plotted on left y-axis with daily precipitation (INSIVUMEH 2012) plotted as bar graph (daily values labeled in mm). The two peaks in water level occurred on the day of heaviest rain (October 12).

There is a 22-day gap in the record from October 27 to November 18, during which the water level decreased approximately 30 cm. On November 18, the water level was visually observed to be 12.6 cm to 13.2 cm above the outflow tube (approximately 3-4 cm above the overflow tube). On January 12, 2012 the water level was observed to be at the level of the overflow tube, approximately 9 cm above the top of the outflow tube.

Water level lowered below the level of the top of the overflow tube on February 2. After the drop below the overflow tube, the former cycles of slow filling and fast chugging began again with less extreme peaks. From February 2 to the end of the record (March 30, 2012), the maximum height variation was only 6 cm (± 1 cm) above the top of the outflow tube.

2.3.2.1.3 Toj Coral Water Height and Precipitation Rate

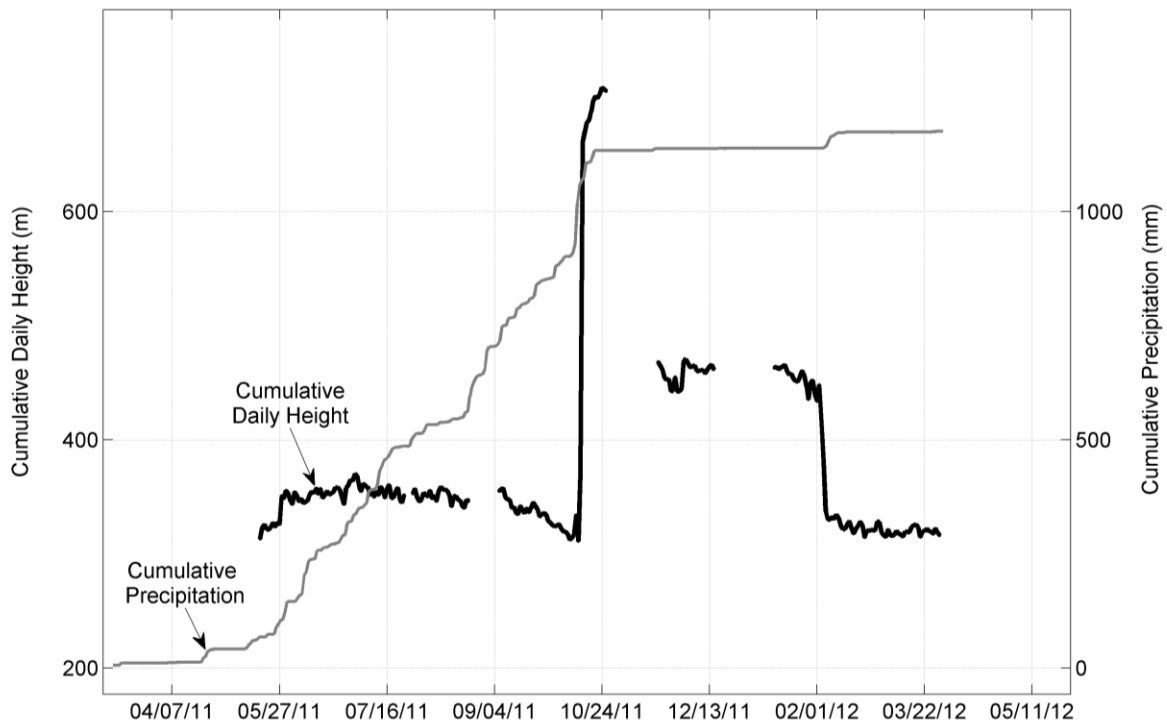


Figure 2.20. All water heights summed over a one-day time period (“cumulative daily height”), normalized to 1-minute recording frequency, shown in black. Daily cumulative precipitation measurements (INSIVUMEH 2012) are shown in gray.

There was a 2-day delay between the peak of Tropical Depression 12E and the water level increase, confirming that spring discharge is responsive to precipitation (see Figure 2.17). To further examine this relationship, the “cumulative” daily water column height was computed by summing all height measurements over 24 hours. This value was then cross-correlated with daily precipitation. The data only qualitatively demonstrate the response of discharge to precipitation, as this cross-correlation does not show any predictable lag between precipitation and cumulative water height.

Average water level was fairly constant from June to mid-September, presumably reflecting relatively constant spring discharge. The average precipitation rate was 6 mm/day over that time period. There was a two-week period in early August where the average precipitation rate was just 0.9 mm/day compared to 6 mm/day in the preceding months. This event may be related to the cessation of large spikes in water level during mid-September to mid-October. There is insufficient data to determine whether this specific event is related to changes in precipitation rate, spring discharge, or some change in downstream system hydraulics.

The lack of correlation between water level height and precipitation does not rule out a predictable relationship between precipitation and spring discharge. Due to the unique geometry of the spring box, water level height is not directly related to spring discharge once flow exceeds the height of the overflow. Additionally, localized precipitation on the north-facing slopes of the Sierra Madre may have varied significantly from the INSIVUMEH data taken in the Quetzaltenango Valley at a distance of 14 km from the site and at 300 m lower elevation.

Even after precipitation ceased on October 20, water levels remained extremely high for at least one week and were elevated above pre-storm levels for 99 days. It is unknown what magnitude of spring discharge increase corresponds with these elevated water levels. Nevertheless, the result implies that larger storms, during which there is prolonged intense rainfall and little insolation or evapotranspiration, are important for short-term aquifer recharge. It also suggests that the Toj Coral aquifer has different flow components, potentially related to storage within the aquifer or different porosities in the aquifer structure. Though little is known about the geologic structure of the area, this is plausible, as the area is comprised of thick porous ignimbrites and pumice deposits as well as fractured andesitic lava flows.

2.3.2.1.4 Aguas Palomas Signal and Stage-Discharge Relationship

With extended discontinuities in the level record and multiple offsets, the Aguas Palomas data do not reveal much about spring discharge, though water levels in the box appear to be relatively constant on average as shown in Figure 2.21. It appears that water level potentially had increased during Tropical Depression 12E and began to decrease or was decreasing by October 27, but data were not recorded and it is unknown how spring discharge responded to the storm.

There is no coherent relationship between combined manual discharge measurements and apparent water level (see Figure 2.22). In particular, apparent water level is substantially higher in January although discharge was measured to be roughly the same ($7.7 \text{ L/s} \pm 0.2 \text{ L/s}$) on 10/27/11, 1/9/12, and 2/14/12. Since the relationship between stage and combined spring discharge is not meaningful, a semi-continuous record of discharge cannot be obtained.

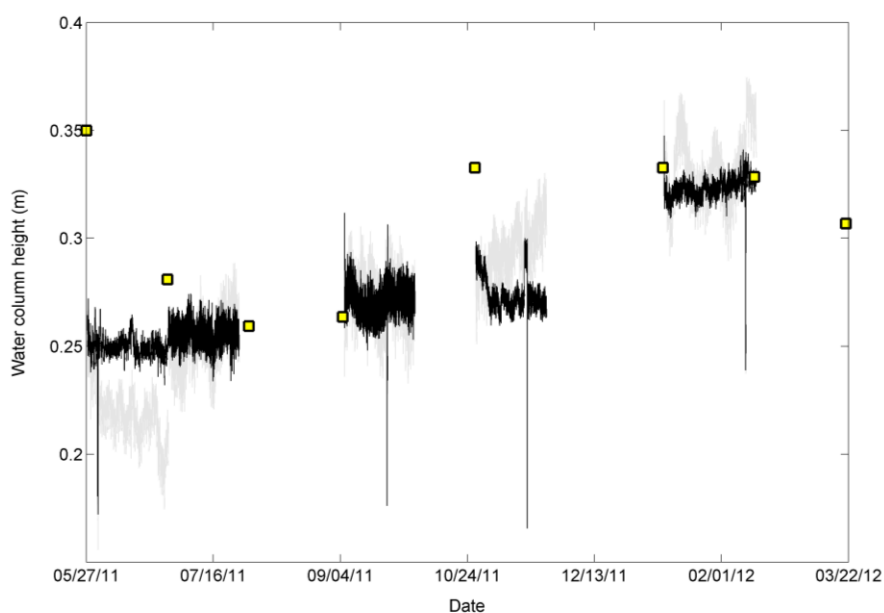


Figure 2.21. Time series of atmospheric correction of Aguas Palomas data, with significant apparent offsets corrected. Raw data is in gray. Combined spring discharges (sum of discharges from springs #1-4) are indicated with yellow squares.

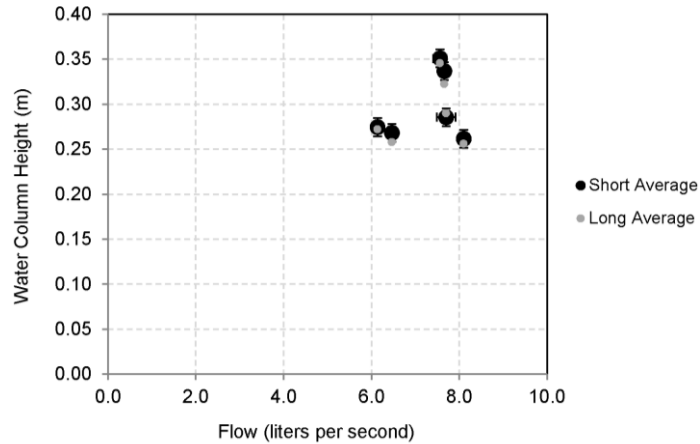


Figure 2.22. Plot of junction box stage versus measured discharge (combined from Aguas Palomas springs #1-4).

There are a number of reasons that the plot may not show a meaningful stage-discharge relationship, including:

- Errors in manual discharge measurement.
- Inconsistent replacement of the data logger chord, resulting in the data logger being suspended at inconsistent heights (including suspension approximately 5 cm lower after October 27, 2011).
- Insufficient variation in junction box stage over the range of measured discharges (less than the accuracy of ± 1 cm achieved with gross atmospheric calibration).
- No fixed relationship hydraulically between junction box stage and spring discharge over the time periods of manual measurement.

The most likely scenario is a combination of some of these factors. The shape of the calibration plot does not change significantly whether short-term data (over the period of measurement) or long-term (daily) averages are used, which implies there were either changes in the gross long-term level of the data logger, changes in the gross long-term water level, and/or errors in manual discharge measurement.

Errors in manual discharge measurement cannot be excluded, especially at the beginning of the field work. The configuration of the junction box made measurement cumbersome for the bucket operator, who had to hunch down inside the junction box well. The timekeeper was above the well and unable to observe the bucket volumes. Initially, the volume of water in the bucket was recorded as reported by the bucket operator. Therefore, it is possible that early reported volumes were inaccurate. This cannot be the only factor confusing the stage-discharge relationship, as later measurements were made with the timekeeper verifying measured volumes.

Disruptions to the data logger level occurred on several occasions (see Figure 2.23 and Figure 2.23), possibly due to inconsistent replacement of the data logger chord. It is difficult to explain the apparent 5 cm increase in water level between 10/27/11 and 01/09/12 due to chord replacement, however. First, there are no notches on the edge of the hatch that might lengthen the chord (see Figure 2.3). Second, the chord was originally placed perpendicular to the edge of the hatch. Replacing the chord to the side would shorten the chord length and produce an apparent decrease in water level.

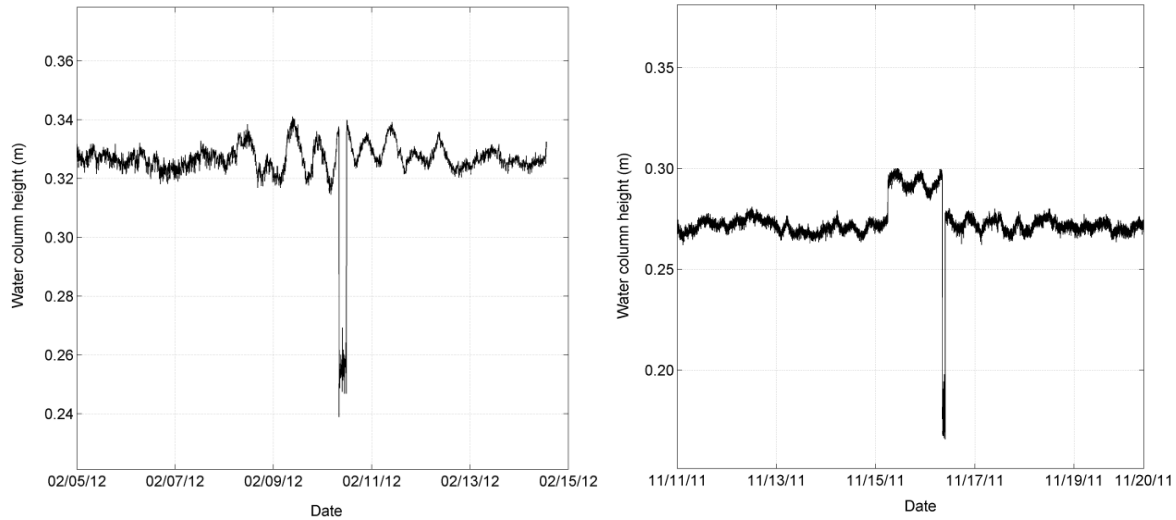


Figure 2.23. Example of two disruptions to the data logger in Aguas Palomas.

One possible scenario for an apparent water level rise due to the chord itself could be raising the lid without weighting the chord against the lip of the hatch. This would give the data logger extra slack on the order of 1 cm, although this would only occur while the hatch was open. It is difficult to propose a reasonable scenario in which the chord is lengthened 5 cm due to misplacement. Even so, the possibility cannot be excluded.

It is also possible that the relationship between junction box stage and spring discharge was inconsistent. One possible explanation for this inconsistency could be water displacement in the box, perhaps from blocks placed in the tank by the municipal plumbers to assist with maintenance. Another possible explanation could be a significant increase in water height in the large distribution tank in the center of town where flow from the Aguas Palomas junction box combines with flow from Toj Coral and Las Barrancas. This hypothesis cannot be assessed, as the geometry of the distribution tank and the history of discharge from Las Barrancas are unknown.

2.3.3 Hydraulic Analysis of Toj Coral System

Due to the lack of reliable manual discharge measurements from the largest Toj Coral spring, a hydraulic analysis was conducted in order to provide an estimate of discharge. The Darcy-Weisbach equation (Equation 1.11) was used in conjunction with a simplified solution of Bernoulli's equation for energy conservation (Equation 1.9b). The two equations are combined in Equation 2.1. An extended description of the assumptions and limitations of this solution is given in section 4.3.3 of Chapter 1.

$$z_1 - z_2 = f_d \frac{L}{D} \frac{v^2}{2g} \quad (2.1)$$

$$\sqrt{(z_1 - z_2) \frac{2g D}{f_d L}} = v \quad (2.2)$$

Flow was estimated from the large Toj Coral spring box to a *caja rompepresión*² in the middle of the flow line at an estimated path distance of 1110 m ± 10 m from the spring box and with an elevation difference of 117 m ± 10 m. An average absolute roughness of 0.004 was assumed for the PVC pipe, giving a relative roughness of 4 x 10⁻⁵ for a nominally 4" pipe. A Darcy friction factor of approximately 0.015 was found using this relative roughness and a Moody diagram. These values yielded the following expression:

$$\sqrt{(117 \text{ m} \pm 10 \text{ m}) \frac{19.6 \text{ m/s}^2}{0.015} \frac{0.1023 \text{ m}}{1113 \text{ m}}} = v$$

$$3.75 \text{ m/s} (\pm 0.15 \text{ m/s}) = v$$

The relationship: $Q = v * a$ yields a discharge of 0.030 m³/s ± 0.02 m³/s or 30 l/s ± 2 l/s for a schedule 40 nominally 4" PVC pipe with an assumed interior diameter of 4.026". This discharge is substantially higher than the discharges measured at the creek bed valve (5.5 l/s – 9.3 l/s). We later learned that only a side stream of the main flow was measured. Additionally, the water level in the spring box dropped to the level of the top of the outflow whenever the creek bed valve was opened. This supports the hypothesis that the valve in the creek bed opened the second conduit without closing off the main conduit.

The cyclical changes in spring box water level are presumably related either to conditions downstream or changes in spring discharge. The longer-period, larger spikes only occur during the wet season (strongest from late May to mid-September), after which they cease. The spikes do not correlate with a particular time of day, but they do correlate generally with precipitation rate. This implies that the larger spikes are related to spring discharge.

The shorter cyclical spikes are much more frequent and continual throughout both the dry and wet seasons whenever there is no overflow in the system. These may be related to system hydraulics or smaller changes in spring discharge.

2.3.4 Technical Limitations and Contributing Social Factors

The usefulness of the data presented in this report was constrained by several technical errors and limitations, including:

Short length of data record and long discontinuities in data. Even if it had been possible to obtain stage-discharge relationships, the length of the data record and gaps within the record would have precluded any robust recession analyses or water balance analyses of the Aguas Palomas dataset. The discontinuities in data could have been avoided with a more appropriate recording resolution of 2 or 3 minutes.

Lack of observations of the physical level of the water-pressure logger relative to water level. The water-pressure logger was clearly disrupted on several occasions in Aguas Palomas, but these disruptions cannot be corrected as no datum was established for the water-pressure logger and water heights were not recorded in the box.

² Translated literally from Spanish, "pressure-breaker box"; known as a "stilling well" in technical English

Lack of accurate barometric compensation at the resolution of the level recording. Though the length of record and offsets are primary constraints, the lack of accurate barometric compensation introduces ± 1 cm of uncertainty into the data and may have been a factor in the unclear stage-discharge relationship in Aguas Palomas.

Inaccurate assumptions about the hydraulics of the water distribution systems. This was a primary issue in the Toj Coral spring box, where the configuration of the distribution system did not allow for a direct discharge measurement. Originally it was assumed that all of the flow from the large Toj Coral spring box could be measured at the valve installed in a creek bed downstream from the spring box, which purportedly was installed by a non-governmental agency for the purpose of monitoring discharge. Based on the configuration of the valve, it is highly unlikely that all discharge was diverted to the side valve. This was not discovered until after fieldwork was completed. Short of retrofitting the system, there was no other place where discharge could be measured.

Based on the author's observations, the root causes of these technical limitations are primarily social in nature, including:

Lack of strong interest locally in the study. Lack of personnel to accompany the author was one of the most important factors limiting the data collection for this study and originally provided impetus for establishing a methodology for measuring discharge semi-continuously with only monthly spring visits. Manual discharge measurement required at least two technicians and local tension over natural resource tenure made it unwise to conduct field activities that appeared to be scientific in nature without a local person.

Due to these same tensions over natural resource tenure, the municipality would not allow non-employees to accompany spring visits. Municipal employees were genuinely overwhelmed by their workloads and it was typical for plans to change in the environmental office with little notice. Therefore, scheduled spring visits were often cancelled or rescheduled in the beginning of the study. Additionally, visits were often under time pressure which most likely contributed to errors.

The lack of interest in the study was most likely based not only on competing immediate priorities and resource constraints, but also more general cultural differences. These differences promoted a lack of confidence in the author as a foreign female and in the value of the study itself.

Long timeline required to implement monitoring. While it was initially difficult to establish monitoring, visits eventually became more routine and better organized. This experience demonstrates that in some cultural contexts, the time required to establish confidence in order to conduct spring discharge studies may be impractical for Peace Corps Masters International (PCMI) student research.

Priority on other projects on the part of the author. With focused project design and data analysis in site, the author might have caught some of the technical errors when there was still time to alter methodologies. Competing local expectations for the author's time, low local interest in the project, reduced access to computing power, and initially unclear project goals/methods were factors that influenced the author.

Lack of technical expertise in the subject area on the part of the author. The author had no background in hydraulics or plumbing prior to the study. Under the constraints of limited supervision, this contributed to some of the fundamental errors in the implementation of the study.

2.4 TECHNICAL AND SOCIAL RECOMMENDATIONS

Water level data loggers did not prove useful in this case in monitoring spring discharge semi-continuously. The technical limitations cited above precluded the observation of a stage-discharge relationship in either Aguas Palomas or Toj Coral. The stage-discharge methodology has been widely applied in springs discharging into open channels and has potential for application in other spring distribution systems. The following are recommendations for the implementation of similar studies in the future.

2.4.1 Research Project Implementation

While the lack of data limits the technical conclusions of this work, this experience highlights many important social factors in implementing a spring discharge study. As discussed above, the majority of technical issues were rooted in social causes. Based on this experience, a spring monitoring project that meets the following characteristics is likely to be more successful:

Liberal and frequent access to springs. The investigator must be able to access the springs reliably, ideally at least once per week. This is not only for the sake of measurement frequency but also for sufficient opportunity to survey spring configuration and trouble-shoot monitoring techniques. The required access will depend on the nature of the study and background of the investigator, but monthly visits are unlikely to provide adequate time for these activities.

Access will likely be favorable at municipal springs where there is already a local technician designated to work with springs on a routine basis (Kucharski 2010), at private springs with willing owners, or where local field assistants can be hired. Access may be difficult in areas with natural resource conflicts or other political tensions.

Adequate time to implement the project. At least one full season of data will need to be collected for recession analyses (Dewandel 2003, Malvicini et al. 2005). Many published studies consider longer data records, whether for recession analyses (Amit et al. 2002, Korkmaz 1990), time series analyses (Lee and Lee 2001), or water balance modeling (Jiang 2007, Xu 1996). Water balance models especially will generally require longer records. Therefore, the scope of the project should be carefully defined for the data available.

While time is required to assess local needs, field work should begin as soon as possible after the initial assessment period in order to identify technical and social issues in implementation ahead of the time period of interest. A significant delay in implementation after the decision to undertake the project is a warning sign that the project is not really a local priority.

The project serves a real need as defined from the local perspective. Ideally the project will intersect both the investigator's technical capabilities and local needs for characterization of spring resources. Realistically this may not always happen, but in the least there needs to be sufficient local interest to meet the minimum requirements for spring access.

It is sometimes instinctual for outsiders to enter a different culture under the auspices of development work and begin to identify solutions to local problems from their own cultural perspective (Chambers 1997). The risk of presenting an idea without first assessing local priorities is that a project may be accepted superficially without sufficient interest for successful implementation, wasting both local and outside resources.

The project is most likely to succeed if it benefits local people or organizations tangibly *from their own perspective*. That benefit may come via the project results or monetary compensation for fieldwork. Though important, the factor of “perceived need” is somewhat subjective and will vary depending on unique context. It may be possible to implement spring monitoring with the interest of just one reliable individual, or it may take an entire committee of officials. There are a number of participatory tools to assist in the objective assessment of local needs (Narayanasamy 2009).

Throughout the process of needs assessment, the investigator should be aware of his/her own perception of the project’s benefits and not impose that perception on others without understanding local priorities. Local counterparts in cultures with indirect communication styles may not want to directly refuse an opportunity, even if they see it as relatively unimportant. Counterparts may also genuinely have initial interest in the project but come to view the cost of the project in time or materials as greater than the value of the project’s benefits, as other opportunities emerge.

This factor often presents a challenge, especially for PCMI students. Students need a research project whether local counterparts perceive a need for the information from that research or not. Students should be aware that there may not be a project that intersects both their academic expertise and locally perceived priorities. In this case, it is most important that the research be technically feasible in terms of data acquisition, even if that means conducting research that is not relevant to the Peace Corps site.

2.4.2 Barometric Compensation

This study demonstrates that high-resolution barometric data is necessary for atmospheric compensation when deploying unvented water-pressure loggers over periods longer than a few hours.

The atmospheric correction method used in this study is based on the assumption that atmospheric pressure changes due to regional weather systems occur linearly in time from day to day. This method is not very accurate but allows for elimination of the most dramatic variations in atmospheric signal based on atmospheric pressure data with limited resolution. The filtering method removes diurnal noise of 2-3 cm but also introduces comparable noise at the edges of the data. The combined method is not useful for applications requiring accuracy greater than ± 1 cm.

If available, the best option for barometric compensation is high-resolution barometric data from a weather station or instrument at a resolution as close to the resolution of the level recording as possible. Another option depending on budget is to deploy a second pressure transducer above water at the same recording resolution as the other data logger. Sorenson and Butcher (2011) advise that the accuracy of compensation provided by barometric loggers may vary based on brand and that some brands appear to perform poorly when air temperature compensation is required. This might also caution against the use of water level loggers for atmospheric logging.

Another option is to deploy vented pressure transducers. These measure only pressure from the water column. Sorenson and Butcher (2011) found that vented sensors were generally more accurate than unvented sensors, although they are not as compact and require the installation of a vent chord.

2.4.3 Recording Resolution

The water-pressure logger instruments were deployed with 15-minute, 1-minute, and 5-minute recording resolutions over different time periods. The recording resolution was set to 1 minute on the rationale that the oscillations in water level in the Toj Coral spring box occurred with a period of approximately 3 minutes. The Aguas Palomas data logger was assigned this same recording resolution. At this resolution the loggers filled every 27 days, and the irregularity of visits meant that there were gaps in the data. The importance of a continuous level record for correcting disruptions was not initially appreciated.

In the case of the Toj Coral spring box, high-resolution recording was necessary to accurately preserve the oscillations in water level (see *Figure 2.24*). However, the 1-minute resolution was excessive: a 2-minute recording resolution would have both preserved the oscillations and prevented gaps in the data. It is more difficult to assess the Aguas Palomas data without more accurate barometric compensation, as there are many apparent changes in water level of 1 cm that are lost when the data is sampled down to 2-minute resolution.

Even so, the water level in the junction box was apparently relatively constant, and it seems unlikely that the formation of the stage-discharge curve would have required such precision. In that case, the 5-minute resolution or higher would have been adequate. Event-based recording may also have been useful in this case. It is a feature of many water-level loggers, such as the Levellogger Gold, that allows for a data point to be stored only when water level changes above a defined threshold.

Though the study had other important errors, one principal lesson of this experience is that logger data should be reviewed and analyzed in the field as it is collected to assure that the recording resolution is appropriate. The original intention was to evaluate the required resolution in the field, but this did not happen due to competing priorities and limited access to computer power.

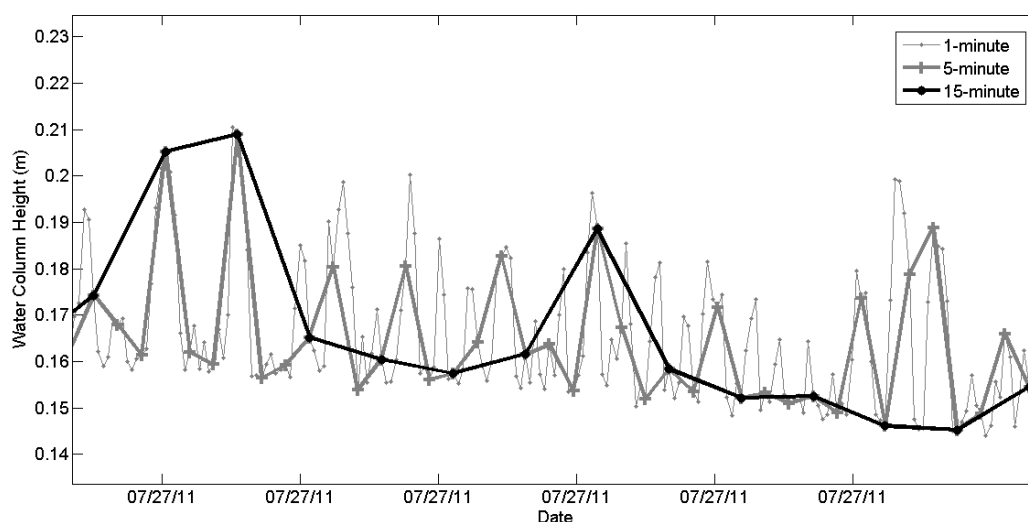


Figure 2.24. Example of hypothetical difference in recording resolutions in Toj Coral: 1-minute data compared to 5-minute and 15-minute resolutions sampled down from 1-minute data.

2.4.4 Data Logger Deployment and Removal

It is crucial when deploying the water-pressure logger that the hydraulics of the system be understood. The entire flow line should be surveyed carefully in order to understand downstream hydraulics and the potential factors affecting water level height in the spring box. In the case of this study, lack of technical expertise and lack of access to the springs contributed to some of the fundamental flaws in the study's implementation.

Another issue constraining the interpretation of the data was a lack of data registering the deployed data loggers to a physical datum. Physical water level measurements were made in Toj Coral during visits but not in Aguas Palomas. In anticipation of potential disruptions to the equipment, the physical water level and data logger level should be recorded at every visit. Ideally, the water-pressure logger should be allowed to equilibrate for 30 minutes after being removed and replaced following data downloading or settings changes.

A final and important deployment consideration is the security of the equipment. Both data loggers were locked in their respective spring boxes with a simple padlock and suspended with nylon cord. While the remote location of many springs will require equipment to be left unattended, a heavier-duty protected padlock and metal cord may have discouraged the theft of the data logger in Aguas Palomas.

2.5 FUTURE WORK

There are obstacles to implementation of a rigorous spring monitoring program in Concepción Chiquirichapa, especially the lack of municipal personnel with time to conduct frequent monitoring. The lack of an adequate methodology for direct discharge measurement in the largest Toj Coral spring is also an obstacle that would need to be addressed. Nevertheless, such a monitoring program could provide important data for municipal resource management.

2.5.1 Natural Resource Management and Water Resources

Future work could examine the link between the management of other natural resources and water resources in order to more effectively direct municipal priorities. In the author's observation, adults in Concepción Chiquirichapa commonly believe that spring discharge is diminishing and that this is one factor in water shortages in the urban center at the end of the dry season/ beginning of wet season (April-May).

Among municipal officials, one common opinion was that deforestation is causing the reduction in water discharge (SEGEPLAN 2010). This attitude is reflective of the widespread agenda of some development agencies operating in Central America that have promoted reforestation/afforestation as a panacea for all environmental problems (Kaimowitz 2004).

Within the last decade, an ongoing reforestation project has been undertaken in the municipal forests concentrating on white pine and alder species (Helvetas ProBosques 2008). Some studies indicate that reforestation and afforestation can actually have negative effects on water supply due to increased evapotranspiration (Bosch and Hewlett 1982, Farley et al. 2005). Ingwersen (1985) documents an exception that may be relevant to Concepción: on the fog-prone Oregon coast, reforestation increases water yield due to interception of water as fog by trees.

A comparison of forest cover change in the catchment areas over past decades could provide some insight into whether deforestation is currently occurring at a significant enough scale to diminish spring resources. Research on specific processes of evapotranspiration, interception, and infiltration in different land cover areas could also clarify the relationship between Concepción's cloud forests and water spring yield.

Another factor in the apparent supply decrease may be increasing demand. Population is currently increasing at an estimated rate of 1.4% (SEGEPLAN 2010) and may be exerting increasing pressure on a relatively constant supply. Long-term monitoring would confirm quantitatively whether spring discharge is in fact diminishing. This data could also help inform an analysis of the utility of undertaking a major overhaul of the distribution system. It would also help the municipality's environmental office to better direct outreach/education efforts to consumers.

2.5.2 Water Balance Analyses and Climate Modeling

Assuming that spring water catchments are topographically controlled, spring sub-catchments were delineated using a flow direction layer in ArcGIS derived from a 30-m resolution DEM. Despite great uncertainty in the model, the Aguas Palomas data roughly fit the runoff and recharge predicted by a simple Thornthwaite-Mather Water Balance (TMWB) analysis (Fish 2011, Dingman 2002). The TMWB model predicts $2.2(10)^5 \text{ m}^3$ of runoff/recharge per year $\pm 0.1(10)^5 \text{ m}^3$ compared

to the $2.3(10)^5 \text{ m}^3$ discharge estimated for Aguas Palomas based on sporadic manual discharge measurements (see Appendix A).

There is clearly much uncertainty in this rough model: most obviously, the Aguas Palomas discharges are interpolated/extrapolated for an entire year based only on eight point measurements over ten months. Additionally, the discharge is likely underestimated, as neither surface runoff nor all springs in that catchment area were measured. The delineation of the topographic catchment area is guesswork, as the aquifer structure may be complex. It is also probable that the precipitation data from INSIVUMEH underestimate the actual precipitation at Aguas Palomas. Additionally, soil field capacity and root zone depth are unknown, though estimated runoff/recharge for the watershed is not very sensitive to these parameters.

Despite these limitations, the analysis does indicate that a more rigorous water balance model with precise data could yield useful information, for example the actual area of the spring catchment. Given a sufficient discharge record, a more robust water balance model might also be used to predict spring yield under varying climate scenarios (Xu et al. 1996, Fish 2011).

2.5.3 Recession Analysis and Time Series Correlations

It is evident from the water level record in Toj Coral that discharge in that spring has baseflow and quickflow components. Therefore, recession analysis of discharge hydrographs from these springs could yield useful information about baseflow characteristics. Time-series correlations might also yield valuable information about lag time between precipitation and discharge. These analyses could help explore the importance of extreme precipitation events in aquifer recharge in both Aguas Palomas and Toj Coral.

Recognition of relationships between precipitation and discharge could have practical applications for seasonal water management, for example for focused campaigns for water conservation around times of greatest anticipated need and for planning for municipal storage of excess water supply during times of abundant discharge.

2.6 CONCLUSIONS

The limited results of this study indicate that extreme precipitation events may play an important role in increasing water spring yields for the municipality, as spring discharge was responsive to Tropical Depression 12E in both catchments of study. From a technical standpoint, discharge monitoring at these springs could yield valuable information about the relationship between precipitation and discharge in each aquifer, and the nature of base-flow recession. Long-term data could also be used in the formation of a water balance model for estimating catchment area and predicting spring discharge yield under varying climate scenarios.

This case study was constrained by several errors and limitations, both social and technical in nature. For one, the study demonstrates the importance of accurate barometric compensation, in-field evaluation of data recording resolution, and the understanding of distribution system hydraulics when deploying water-pressure loggers for long-term water level measurement.

The social limitations of the study were many. These lessons can serve to prepare other Peace Corps Master's International students or other researchers planning to conduct spring discharge studies in an intercultural context. In particular, the experience highlights the need for strong local support of research, the long length of time that is required to gain that buy-in, and the importance of defining a clear and feasible project idea from the outset.

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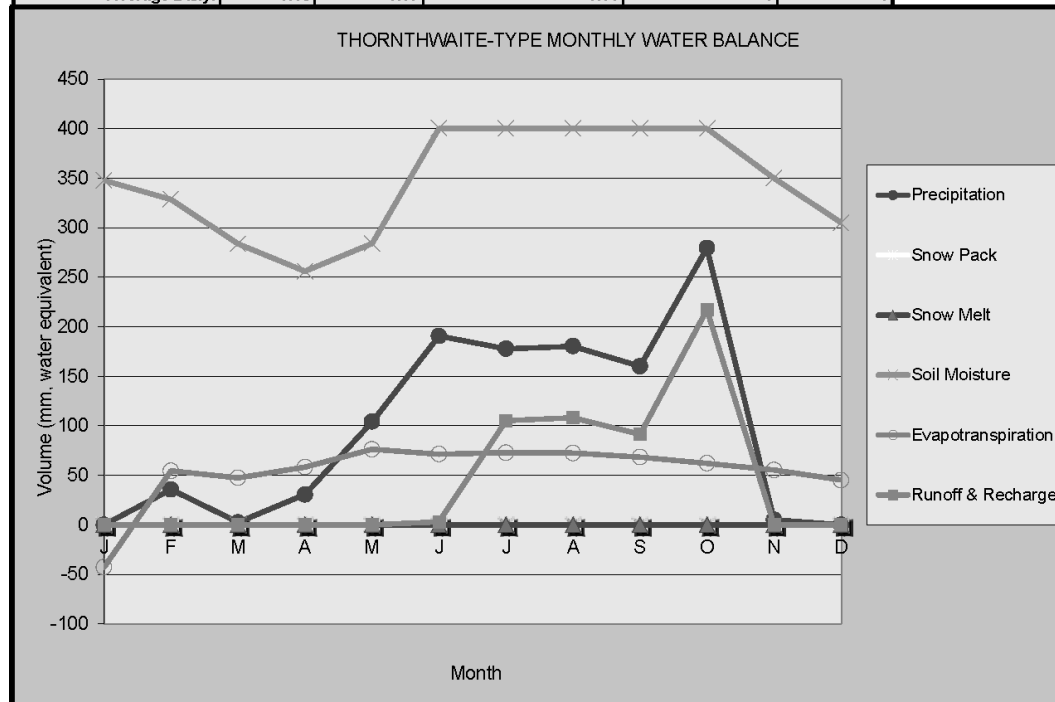
2.8 APPENDICES

2.8.1 Appendix A: Thornthwaite-Mather Water Balance Calculations

| THORNTHWAITE-TYPE MONTHLY WATER-BALANCE MODEL | | | | | | | | | | | | | | | |
|--|--------|--------|-------------------------|-----------------------------|--------------------------------------|-------|---|---------------------------------------|-----------------|--------|-----------------------------|--------|---------|---------|--|
| Based on a spreadsheet titled, "ThornEx.xls," by S.L. Dingman, Physical Hydrology, 2nd Ed. | | | | | | | See Box 7-3. PET computed via Hamon equation [Eqn.(7-63)]. | | | | | | | | |
| Cell Color Codes: Input Data | | | | Computed Values (Protected) | | | | Titles, Labels, and Units (Protected) | | | | | | | |
| Data Sources: INSIVUMEH | | | | | | | | | | | | | | | |
| Year: May 2011 to March 2012 | | | | | Soil Field Capacity, θ_{fc} : | | | | 0.40 | | Root Zone Depth, Z_{rz} : | | | 1000 mm | |
| Location of Climate Data: Labor Ovalle Quetzaltenango | | | | | Latitude: 14.8 | | | | decimal degrees | | $SOIL_{max}$: | | | 400 mm | |
| Previous December Snowpack, $PACK_0$: | | | 0 mm (water equivalent) | | 0.26 | | | | rad | | $SOIL_0$: | | | 400 mm | |
| Month: | J | F | M | A | M | J | J | A | S | O | N | D | Average | | |
| Julian Day, J : | 15 | 45 | 74.5 | 105 | 135.5 | 166 | 196.5 | 227.5 | 258 | 288.5 | 319 | 349.5 | | | |
| Day Angle, Γ (radians): | 0.241 | 0.757 | 1.265 | 1.790 | 2.315 | 2.840 | 3.365 | 3.899 | 4.424 | 4.949 | 5.474 | 5.999 | | | |
| Declination, δ (radians): | -0.371 | -0.232 | -0.039 | 0.165 | 0.328 | 0.406 | 0.377 | 0.247 | 0.058 | -0.147 | -0.319 | -0.406 | | | |
| Day Length, D (hr): | 11.2 | 11.5 | 11.9 | 12.3 | 12.7 | 12.9 | 12.8 | 12.5 | 12.1 | 11.7 | 11.3 | 11.1 | 12 | | |
| WATER BALANCE | | | | | | | | | | | | | | | |
| Temperatures in degrees Celcius, Water-balance terms in mm water equivalent. | | | | | | | | | | | | | | | |
| Month: | J | F | M | A | M | J | J | A | S | O | N | D | Annual | | |
| Monthly Precipitation, P : | 0 | 36 | 3 | 30 | 104 | 191 | 178 | 180 | 160 | 279 | 5 | 0 | 1166 | | |
| Mean Monthly Temperature, T : | 13.6 | 13.6 | 14.0 | 15.9 | 16.5 | 15.2 | 15.6 | 15.9 | 15.5 | 14.5 | 14.1 | 13.4 | 15 | | |
| Melting Factor, F : | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1 | | |
| Precipitation as Rain, $RAIN$: | 0 | 36 | 3 | 30 | 104 | 191 | 178 | 180 | 160 | 279 | 5 | 0 | 1166 | | |
| Precipitation as Snow, $SNOW$: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| Snow Pack, $PACK$: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| Snow Melt, $MELT$: | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| Water Input, $RAIN+MELT$: | 0 | 36 | 3 | 30 | 104 | 191 | 178 | 180 | 160 | 279 | 5 | 0 | 1166 | | |
| Potential Evapotranspiration, PET : | 56 | 58 | 61 | 72 | 76 | 71 | 73 | 72 | 68 | 62 | 59 | 55 | 784 | | |
| Net Water Input, $RAIN + MELT - PET$: | -56 | -22 | -59 | -41 | 28 | 119 | 105 | 108 | 92 | 217 | -54 | -55 | 381 | | |
| Soil Moisture, $SOIL$: | 348 | 329 | 284 | 256 | 284 | 400 | 400 | 400 | 400 | 400 | 350 | 305 | 346 | | |
| Change in Soil Moisture, $\Delta SOIL$: | 43 | -19 | -45 | -28 | 28 | 116 | 0 | 0 | 0 | 0 | -50 | -45 | 0 | | |
| Actual Evapotranspiration, ET : | -43 | 55 | 48 | 58 | 76 | 71 | 73 | 72 | 68 | 62 | 55 | 45 | 641 | | |
| Recharge & Runoff, $RAIN+MELT-ET-\Delta SOIL$: | 0 | 0 | 0 | 0 | 0 | 3 | 105 | 108 | 92 | 217 | 0 | 0 | 525 | | |
| Month: | J | F | M | A | M | J | J | A | S | O | N | D | Annual | | |
| Monthly Precipitation (inches): | 0 | 1.4 | 0.1 | 1.2 | 4.1 | 7.5 | 7 | 7.1 | 6.3 | 11 | 0.2 | 0 | 45.9 | | |
| Mean Monthly Temperature (F): | 56.4 | 56.5 | 57.2 | 60.7 | 61.7 | 59.4 | 60.1 | 60.6 | 59.9 | 58.1 | 57.3 | 56.1 | 58.7 | | |
| Observed Ave. Monthly Streamflow (cfs): | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.0 | | |

Water balance calculations for Aguas Palomas springs, considering a topographically-delineated catchment area of 0.159 mi² (0.412 km²).

| Watershed Calculations | Area: 0.159 sq. miles | | | Estimated | Observed |
|------------------------|-----------------------|-------------|------------------|---------------|----------|
| Month | P (inches) | ET (inches) | RO+RCHG (inches) | RO+RCHG (cfs) | RO (cfs) |
| J | 0.0 | -1.7 | 0.0 | 0 | 0 |
| F | 1.4 | 2.1 | 0.0 | 0 | 0 |
| M | 0.1 | 1.9 | 0.0 | 0 | 0 |
| A | 1.2 | 2.3 | 0.0 | 0 | 0 |
| M | 4.1 | 3.0 | 0.0 | 0 | 0 |
| J | 7.5 | 2.8 | 0.1 | 0 | 0 |
| J | 7.0 | 2.9 | 4.1 | 1 | 0 |
| A | 7.1 | 2.8 | 4.3 | 1 | 0 |
| S | 6.3 | 2.7 | 3.6 | 1 | 0 |
| O | 11.0 | 2.4 | 8.6 | 1 | 0 |
| N | 0.2 | 2.2 | 0.0 | 0 | 0 |
| D | 0.0 | 1.8 | 0.0 | 0 | 0 |
| Average Annual: | 45.9 | 25.2 | 20.7 | | |
| Average Monthly: | 3.83 | 2.10 | 1.72 | | |
| Average Daily: | 0.13 | 0.07 | 0.06 | 0 | 0 |



ESTIMATE OF YEARLY DISCHARGE/RUNOFF - AGUAS PALOMAS

THORNWAITE MODEL

| Unit | <u>Yearly RO/RCHG</u> | <u>Catchment Area</u> | <u>Yearly Flow (Predicted)</u> |
|-------------|-----------------------|-----------------------|--------------------------------|
| in | 20.64 in | | <u>Thornwaite Model</u> |
| km^2 | | 0.411 km^2 | |
| m, m^2, m^3 | 0.5243 m | 411000 m^2 | 2.2E+05 m^3 |

MEASURED ESTIMATE

| <u>Date of Measurement</u> | <u>Discharge Measurement (L/s)</u> | <u>"Nearest-Neighbor" Time Interval for Discharge Measurement</u> | <u>Days in Interval</u> | <u>Total Discharge Over Period Between Measurements (L)</u> | <u>Total Discharge Over Period Between Measurements (m^3)</u> |
|----------------------------|------------------------------------|---|-------------------------|---|---|
| 5/27/2011 | 8.1 | 4/1/2011 - 6/12/2011 | 72 | 5.05E+07 | 5.0E+04 |
| 6/28/2011 | 6.5 | 6/12/2011 - 7/14/2011 | 32 | 1.79E+07 | 1.8E+04 |
| 7/30/2011 | 6.0 | 7/14/2011 - 8/17/2011 | 34.5 | 1.80E+07 | 1.8E+04 |
| 9/5/2011 | 6.1 | 8/17/2011 - 10/1/2011 | 44.5 | 2.36E+07 | 2.4E+04 |
| 10/27/2011 | 7.7 | 10/1/2011 - 12/3/2011 | 63 | 4.21E+07 | 4.2E+04 |
| 1/9/2012 | 7.7 | 12/3/2011 - 1/27/2012 | 55 | 3.64E+07 | 3.6E+04 |
| 2/14/2012 | 7.6 | 1/27/2012 - 3/3/2012 | 36 | 2.35E+07 | 2.4E+04 |
| 3/21/2012 | 7.1 | 3/3/2012 - 3/31/2012 | 28 | 1.71E+07 | 1.7E+04 |
| | | | 365 | 2.29E+08 | 2.3E+05 |

2.8.2 Appendix B: Permissions

The following correspondence establishes permission to use orthophotos (MAGA 2006, with credit to SEGEPLAN/SINIT/IDE for WMS service) as a base map in Figure 2.2.



Stephanie Tubman <sctubman@mtu.edu>

Uso de la informacion del SEGEPLAN del WMS

3 messages

Stephanie Tubman <sctubman@mtu.edu>
To: edwin.cabnal@segeplan.gob.gt

Thu, Mar 28, 2013 at 5:51 PM

Estimado Sr. Cabnal,

Tengo una pregunta sobre el uso de la informacion que se puede acceder por medio del WMS en el sitio de la IDE de SEGEPLAN. Estoy escribiendo un informe en la Michigan Tech University sobre la hidrologia de la municipalidad de Concepcion Chiquirichapa, Quetzaltenango, y como parte de la investigacion yo he usado algunos ortofotos como fondo de varios mapas.

Mi pregunta es si necesito algun permiso especial para publicar dicha informacion en mi informe. El uso de la informacion es sin fines lucrativos. Naturalmente yo le daria los creditos respectivos al SINIT / SEGEPLAN, y al IGN.

Le agradezco de antemano su atencion y estare a la espera de su respuesta.

Steph

--

Stephanie Tubman
MS Candidate, Geology
Department of Geological and Mining Engineering and Sciences
Michigan Technological University
Houghton, MI 49931

DOW 209

Edwin Wilfredo Cabnal Hernández <edwin.cabnal@segeplan.gob.gt>
To: Stephanie Tubman <sctubman@mtu.edu>

Fri, Mar 29, 2013 at 12:01 PM

Estimada Srita. Tubman, buenos días.

Con los créditos necesarios son suficientes. No necesita de un permiso especial.

Saludos.

Edwin Cabnal

From: Stephanie Tubman [sctubman@mtu.edu]
Sent: Thursday, March 28, 2013 3:51 PM
To: Edwin Wilfredo Cabnal Hernández
Subject: Uso de la informacion del SEGEPLAN del WMS
[Quoted text hidden]
Edwin Wilfredo Cabnal Hernández

Especialista en Sistemas de Información Geográfica / Dirección Ejecutiva de la Subsecretaría de Planificación y