

A Conceptual Model of Groundwater Flow to Springs in Ban-Utod and Cagnonoc
Watersheds, Baybay, Leyte, Philippines

By

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Submitted in partial fulfillment of the requirements

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This report titled, "A Conceptual Model of Groundwater Flow to Springs in Ban-Utod and Cagnonoc Watersheds, Baybay, Leyte, Philippines," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN ENVIRONMENTAL ENGINEERING.

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External Data Sources

Data Type	Data Source
Flow rates estimates (2005)	Baybay Water District Baybay City, Leyte Philippines
Topographical Map	National Mapping and Resource Information Authority (NAMRIA) Philippines
Total Monthly Rainfall, Monthly Mean of Relative Humidity (%) (8am/2pm), Monthly Mean Air Temperature (°C) Minimum and Maximum (8am/2pm) at Visayas State University (1988-2009)	PAGASA ARGOMET STATION VSU (ViSCA), BAYBAY CITY, LEYTE PHILIPPINES

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Summary

Population growth and resource extraction are increasing pressure on the springs that provide water for Baybay City, Leyte, Philippines. However, information regarding the spring recharge and aquifer is limited. The goal of this report is to qualitatively and quantitatively describe the recharge area and aquifer. Once accomplished, inferences can be made to improve spring production and protection.

Three groups of geographically clustered springs were studied (a total of eleven springs). Two clusters, Busay Springs (five springs) and Kawayan Spring, are within the Cagnonoc Watershed and Hayas Springs (five springs) are within the Ban-Utod Watershed located about five kilometers away. The watersheds are mountainous, tropical forest.

To create the conceptual model, spring discharge, rainfall data, water chemistry, and water isotopes were collected and analyzed from one spring in each cluster. Isotope analysis suggests that all the spring water originates from rainfall. The Thornthwaite-Type Monthly Water Balance Model (TWBM) estimated the minimum recharge area at 168 ha (45% of Cagnonoc Watershed) and 72 ha (15% of Ban-Utod watershed). Based on catchment area delineation, the plausible recharge areas for Hayas Springs are within the near-slope area of the watershed, and the plausible recharge areas for Busay and Kawayan extend beyond the near-slope area of the watershed. Cross-correlation analysis approximated the time lag between rainfall and spring discharge of three springs (Busay 4, Kawayan, and Hayas 5) at 29, 24, and 16 months, respectively.

A basic flow model was constructed by compiling the various information of this study. Kawayan and Busay Springs are part of relatively large basalt aquifers. Evidence supporting this is little variability in monthly average discharge despite several months of no recharge. Hayas 5 is part of smaller basalt aquifer with highly variable discharge that responds to the highly variable recharge. Based on isotope results, Hayas 5 appears unconnected hydraulically to the rest of Hayas Springs. The general flow model has two components: a fast-moving rainfall-event component and a more consistent base flow component. Kawayan and Busay have large base flow components, which indicate low transmissivity. Hayas has a lesser base flow component indicating high transmissivity.

In applying lessons from this model, future resource development planning needs to include the variability of spring production. Forecasting spring production with meteoric data is a possible tool in drought readiness. Critical is the protecting of the recharge area because disturbance of the watershed could adversely quickly affect spring water quality. It is plausible the upslope area from the springs is the recharge area. A water budget assessment of the watersheds would improve certainty of the recharge area being within watershed

1 Introduction

Springs are the endpoints of a groundwater-flow system. They are the only direct natural observation of groundwater. These points are where groundwater flows out of the earth creating streams or rivers. Scientifically, springs are described as points where an abrupt change in geology and/or surface topography results in the water table being above the topography, causing groundwater to surface (Bryan 1919). See Appendix A: Visual Classification of the Springs for more details about different spring formations.

The basics of a spring-aquifer system are illustrated in Figure 1. Precipitation enters the aquifer at the recharge area. The water then travels along the porous aquifer, chemically reacting with the various rock types and soils before exiting the aquifer at the spring. The aquifer is often a “black box” of unknowns due to limitations in knowledge of subsurface geology (Manga 2001).

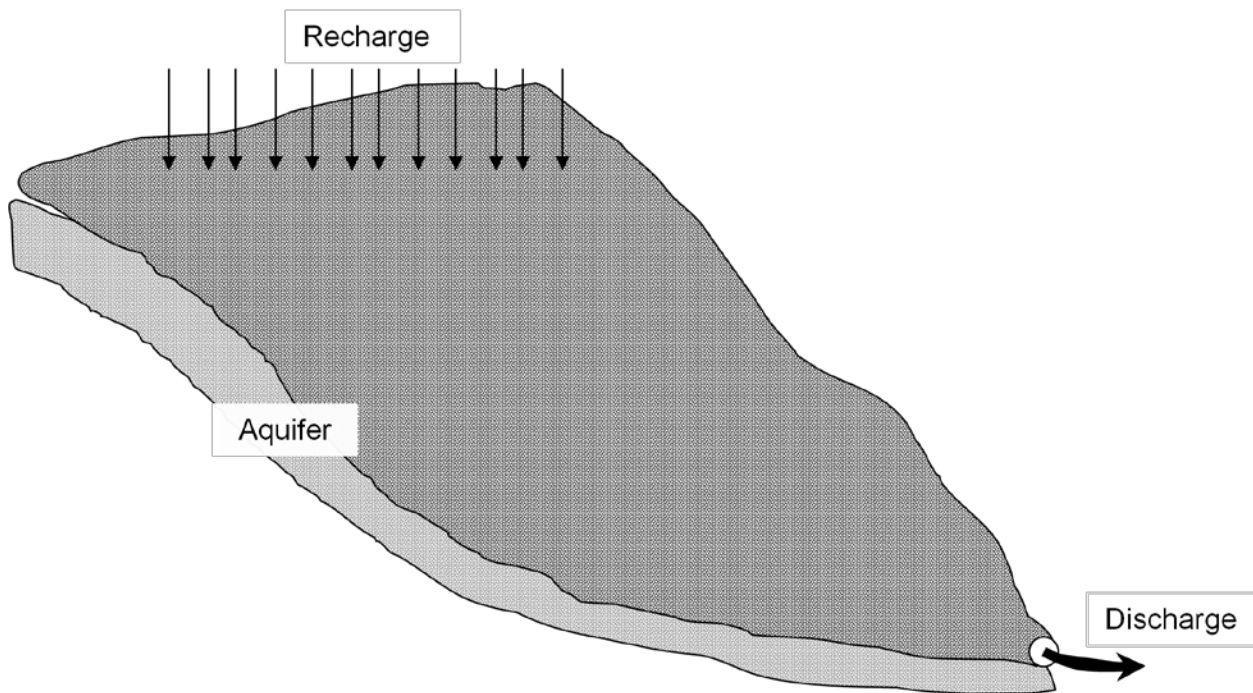


Figure 1. Diagram of basic spring-aquifer system

The spring-water supply in Baybay City on the island of Leyte in the Philippines is an example of a black- box aquifer-spring system. Although some of the springs have been providing water for the community for several decades (Busay 5 spring box is dated 1925), existing information about the springs is limited to a generalized geologic map, some basic

water chemistry data, and spring flow estimates. Yet, these springs along with many springs in the area, are the community's main water supply.

I served as a U.S. Peace Corps Volunteer in Baybay City working with government agencies, communities, and NGOs from 2007-2009. The motivations for the study outlined in this report resulted from perceived needs to address issues specific to the location, including: complaints by water district members about spring production, growing demand on water resources, potential mining in the mountains, and illegal logging in the mountains. An understanding of the recharge area and aquifers was seen as a way to improve management decisions in response to these issues.

1.1 Project site

1.1.1 Location

The Philippines is an archipelago located in Southeast Asia and is composed of more than 7,100 islands (Figure 2). The Philippines islands are grouped into three areas: Luzon, Visayas, and Mindanao. Luzon is the large island in the north and Mindanao is the large island in the south. The Visayas are numerous mid-size islands in the middle of the country. Leyte is located in the eastern part of the Visayas and is where this study was conducted (Figure 2).

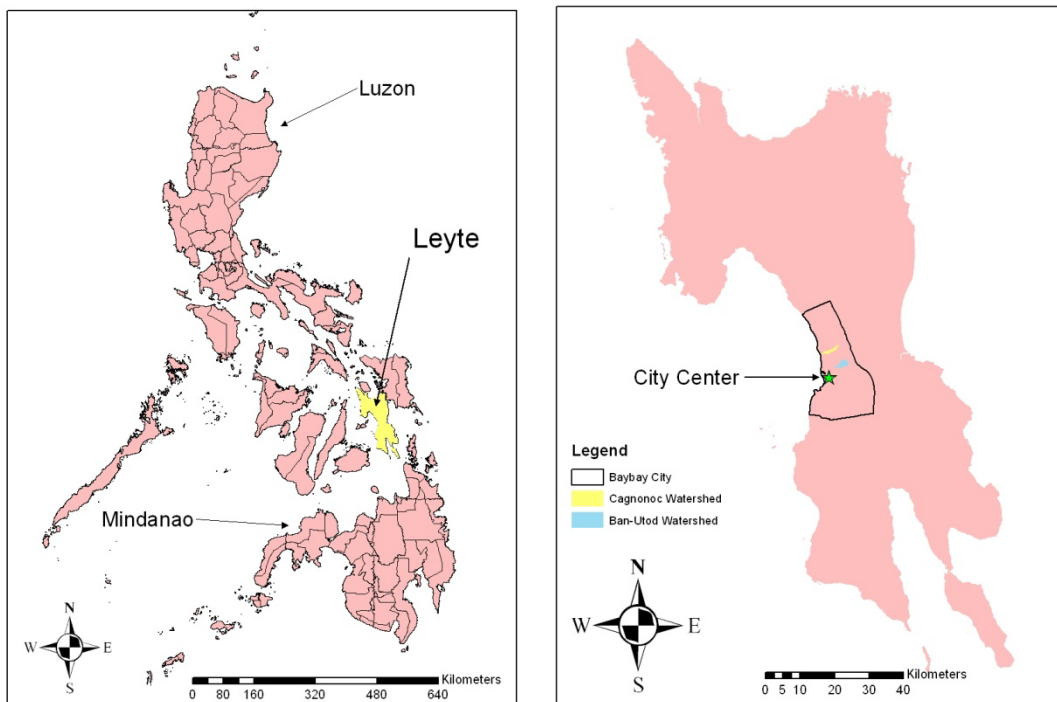


Figure 2. Map of Philippines and Leyte (adapted from Map Library 2010)

The Leyte Cordillera is oriented in a North-South direction and is the geographical divide of the island. The springs in this study are located in watersheds on the west side of the Leyte Cordillera. The watersheds are about halfway along the mountain range and their waters eventually spill into the Camote Sea. The rivers in these watersheds are locally known as the Cagnonoc River and Ban-Utod River. The watersheds are approximately five kilometers apart.

The watersheds are located within the city boundaries of Baybay, Leyte. The springs and river within these watersheds provide the water for the city center and adjacent *barangays* (rural villages). Both watersheds are north of the city center. The Ban-Utod Watershed is approximately one kilometer north of the city center and the watershed boundaries are within Barangays: Kansungka, Villa MagAso, Maganhan, and Igang. The Cagnonoc Watershed is within the boundaries of Barangay Patag.

1.1.2 Geology/Geomorphology

The geology of Leyte is summarized in a broad geological map by the Department of Environment and Natural Resources [DENR]. The surface geology of the watersheds is described as primarily Pliocene-Miocene “intermediate conglomerate & pyroclastics” and Miocene “andesitic, basaltic, & dacitic & breccias” (DENR 1987). Soil analysis on the mountain range classified the parent rock of the soils in the area as primarily basaltic from the Lower Pleistocene to Pliocene age (Asio 1996).

The geomorphology of the region was interpreted from radar satellite imagery (Figure 3). The movement along the northwest-to-southeast-trending Leyte Fault has resulted in uplift and associated volcanic activity that created much of the island (Asio 1996). The remnants of the historical volcanoes have eroded, creating the present alluvial fans (Asio 1996). Streams on the west side of the island generally follow parallel drainage patterns except where secondary faults occur. The west side appears to have eroded less as the mountain valleys are steep V-shaped valleys. The watersheds are at consistent gradients until reaching the upper region of the watersheds (Figure 4). The topographic catchment areas of Cagnonoc and Ban-Utod Watershed are 370 ha and 490 ha, respectively.

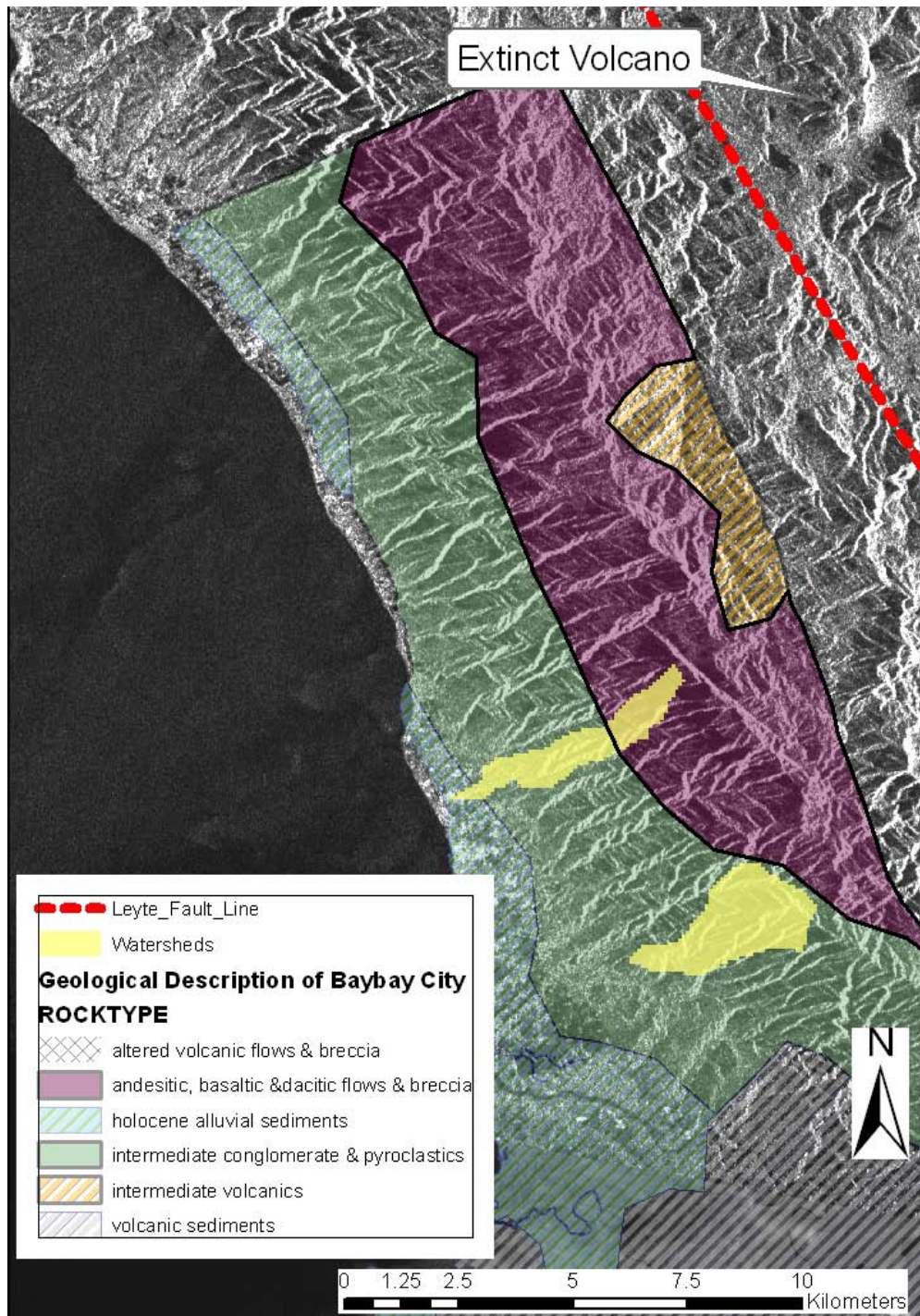


Figure 3. Radar image of the project area with geological descriptions of Baybay City, Leyte (RADARSAT data from Alaska Satellite Facility (©CSA 1996), Geological data from DENR 1987).

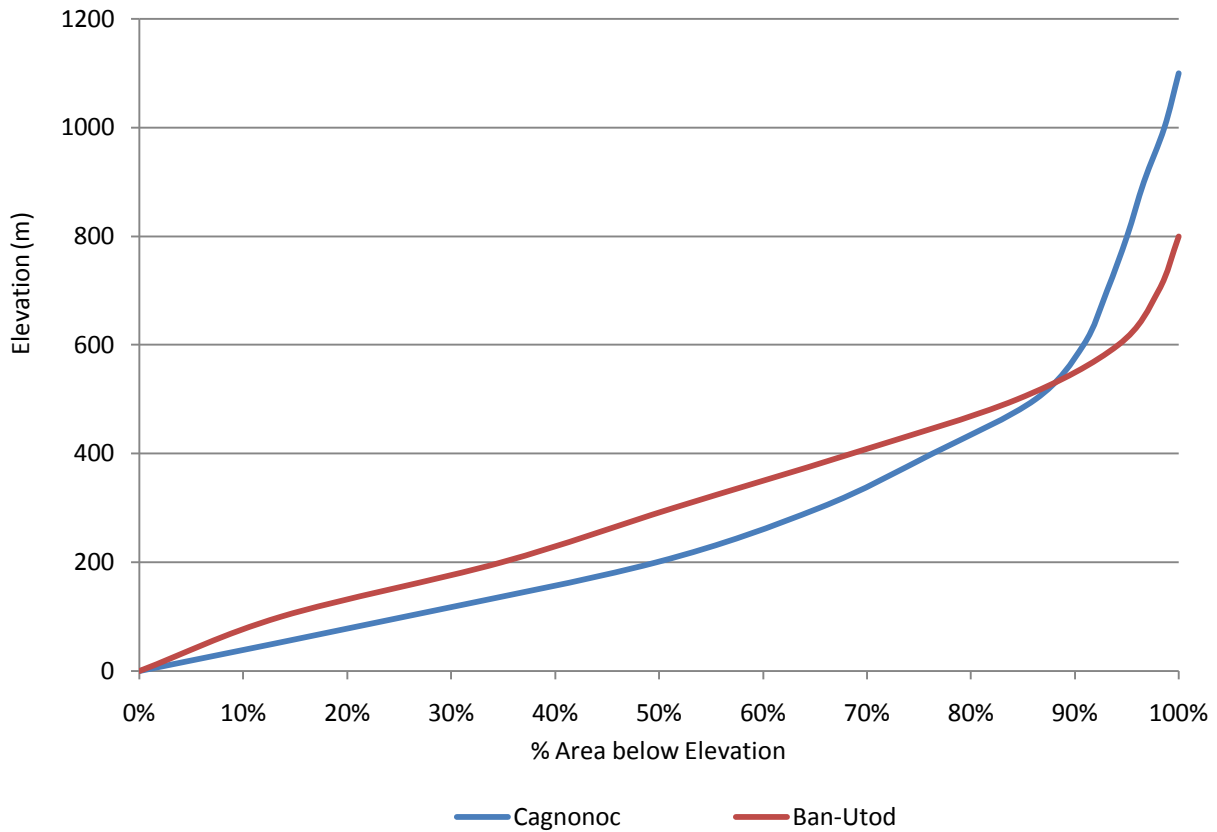


Figure 4. Hypsometric curve of Cagnonoc and Ban-Utod Watershed.

1.1.3 Climate

The Mean annual rainfall from 1988 through 2009 is 2,900 mm, and the mean rainfall is greater than 100 mm for each month (Figure 5). The least amount of rain occurs from March to May, while October to January rainfall averages more than 300 mm per month. The standard deviation of monthly rainfall ranges from 90 to 180 mm. The average frequency of tropical typhoons over Leyte is five typhoons in three years (United Nations Framework Convention on Climate Change [UNFCCC] 1999).

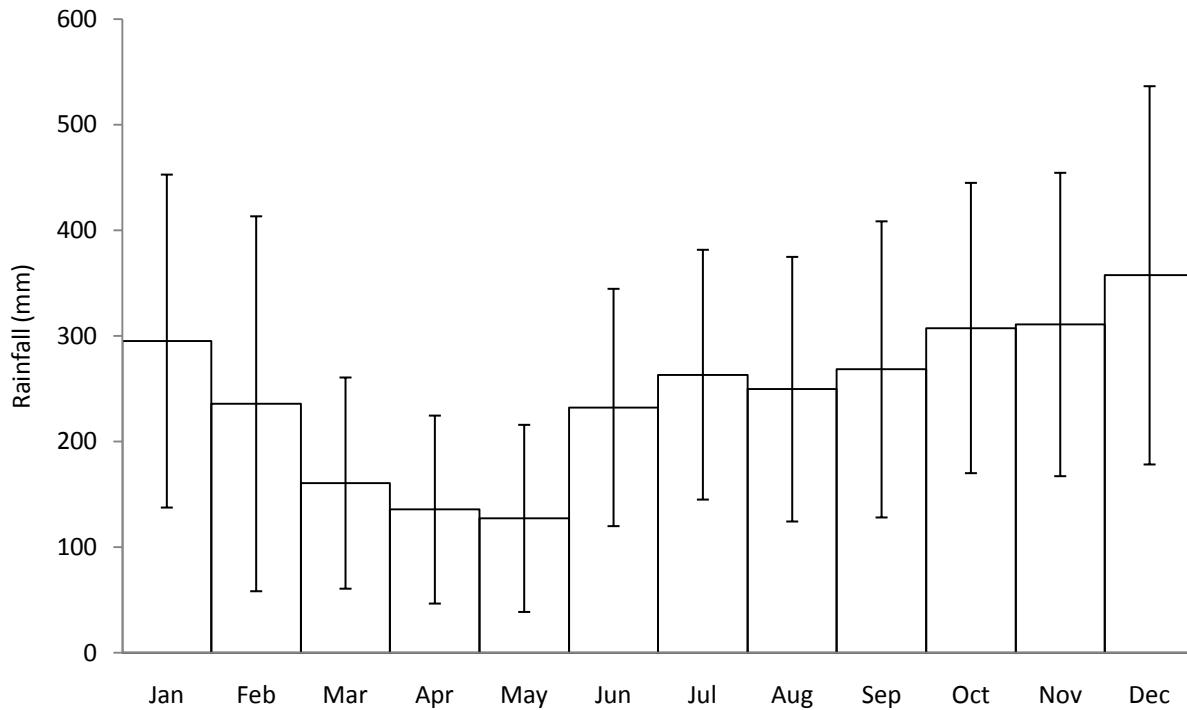


Figure 5. Mean monthly rainfall (1988-2009). Vertical bars represent standard deviations of the mean.

Baybay, Leyte is a consistently warm tropical climate with mean monthly temperatures ranging from 28.3°C in May to 26.9°C in December (Figure 6) and mean relative humidities from 70-80% (Figure 7). Daily temperature measurements ranges from 35°C and to 19°C.

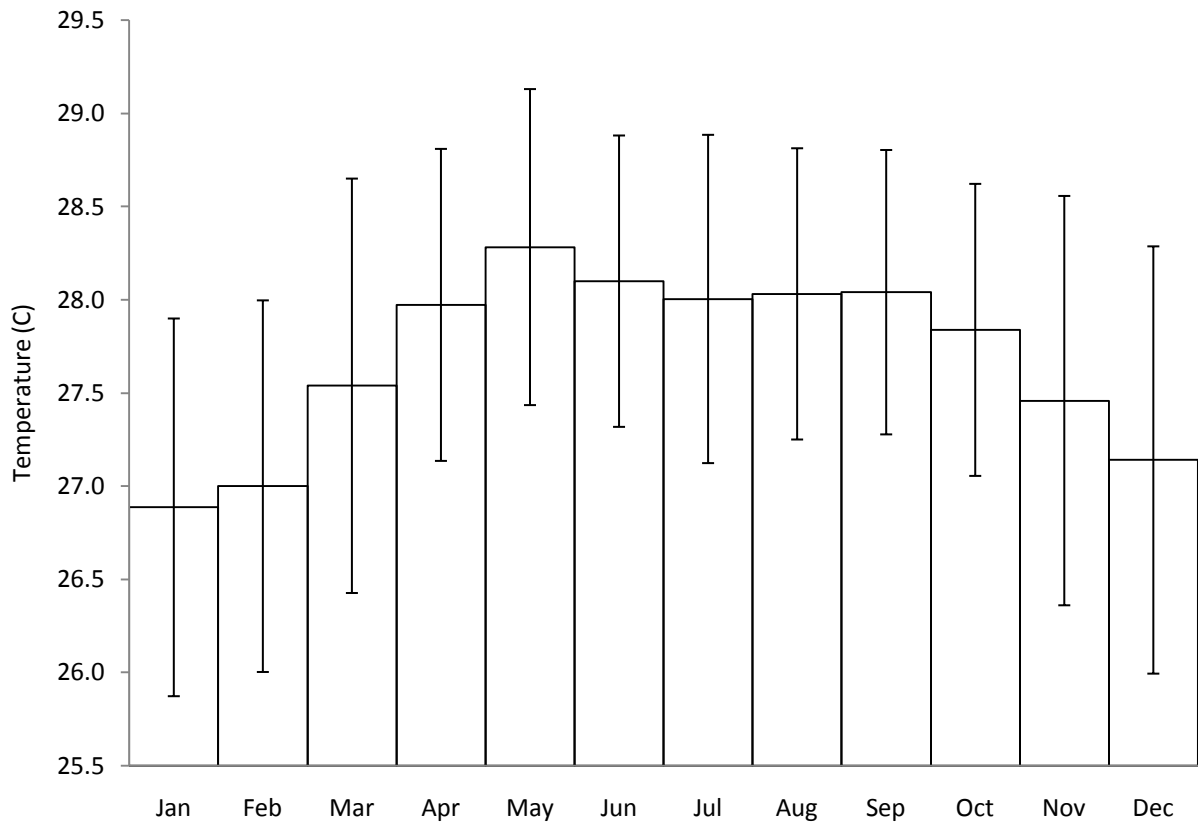


Figure 6. Mean monthly temperature (1988-2009). Vertical bars represent standard deviations of the mean.

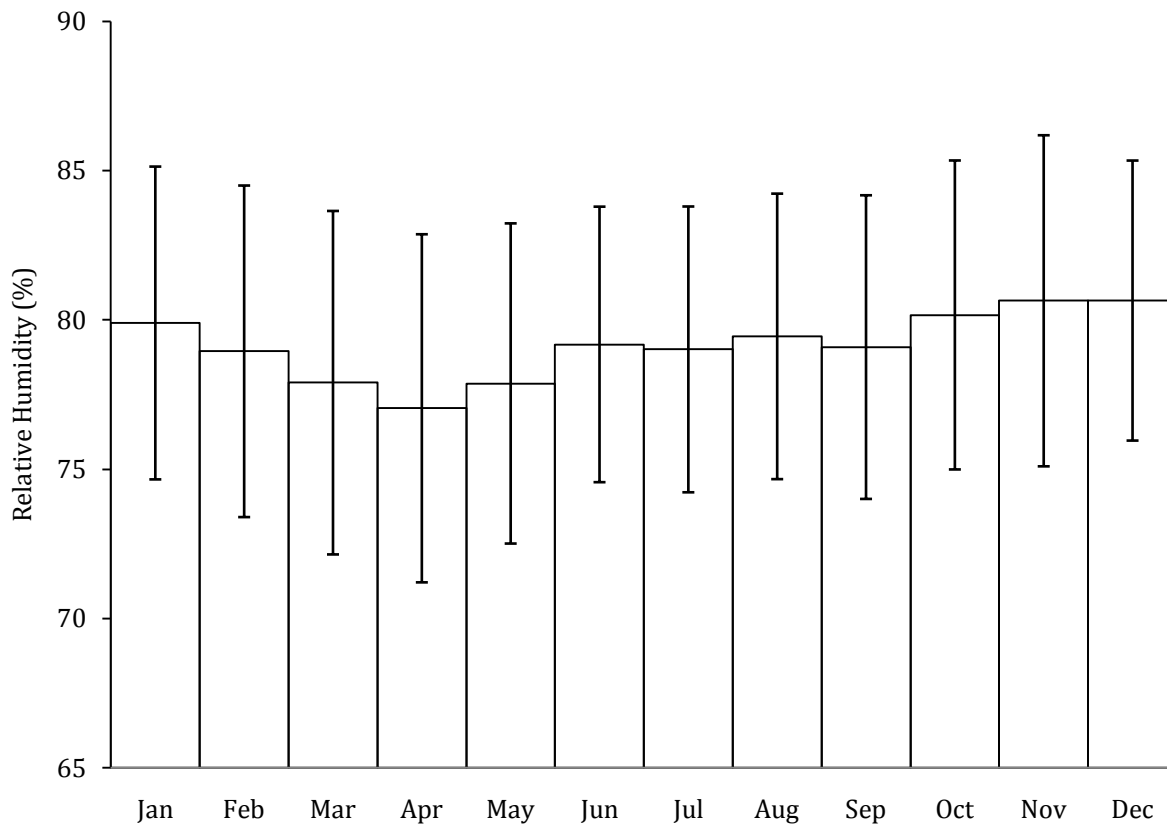


Figure 7. Mean relative humidity (1988-2009). Vertical bars represent standard deviations of the mean.

1.1.4 Vegetation

The major vegetation type of each watershed is dense forest with patches of cultivated crops such as abaca, coconuts, and various root crops (Figure 8 and Figure 9). A study conducted by the Community Environment and Natural Resource Office (CENRO) in 1998 estimated that 60% of the Cagnonoc Watershed is open canopy with mature trees. Cultivated brushland/grassland and coconut plantation are 30% and 10%, respectively. The cultivated areas are at the lower end of the watershed. Based on personal observations, the vegetation of Ban-Utod is similar to Cagnonoc Watershed but may differ slightly on the percentages of vegetation cover types.



Figure 8. Forest in the upper regions of the Cagnonoc Watershed. (Photo by author)



Figure 9. Cultivated plants cover the lower regions of Cagnonoc Watershed. (Photo by author)

1.1.5 Spring Description

Eleven perennial springs were involved in this study. These springs are geographically clustered into three groups: Busay, Kawayan, and Hayas. All springs are encased in spring boxes and obscured from direct observation. Flow rate estimates and spring elevations are listed in Table 1.

Table 1. Spring Discharge Estimates

Spring Cluster	Number	Elevation (m)	Discharge Rate* (L/s)
Busay	1	80	5
	2	75	31
	3	68	12
	4	50	3
	5	69	7
Kawayan		28	7
Hayas	1	58	10
	2	58	2
	3	58	2
	4	58	6
	5	69	10

*based on 2005 Baybay Water District survey

1.1.5.1 Busay Springs

Busay Springs are located in the Cagnonoc Watershed (Figure 10). The springs are approximately 500 meters upslope from the base of the mountain. All springs, except for Busay 4, are approximately 20 to 30 meters above the river. Busay 4 is approximately four to five meters above the river. Springs 1, 2, 3, and 4 are located on the north side of the river and Spring 5 is on the south side. Flow paths occur through the fractured igneous rock and conglomerates. Smaller nondescript springs in the area have water spraying out of fissures in the rock layers. Classification of these springs is either fissure springs or artesian springs.

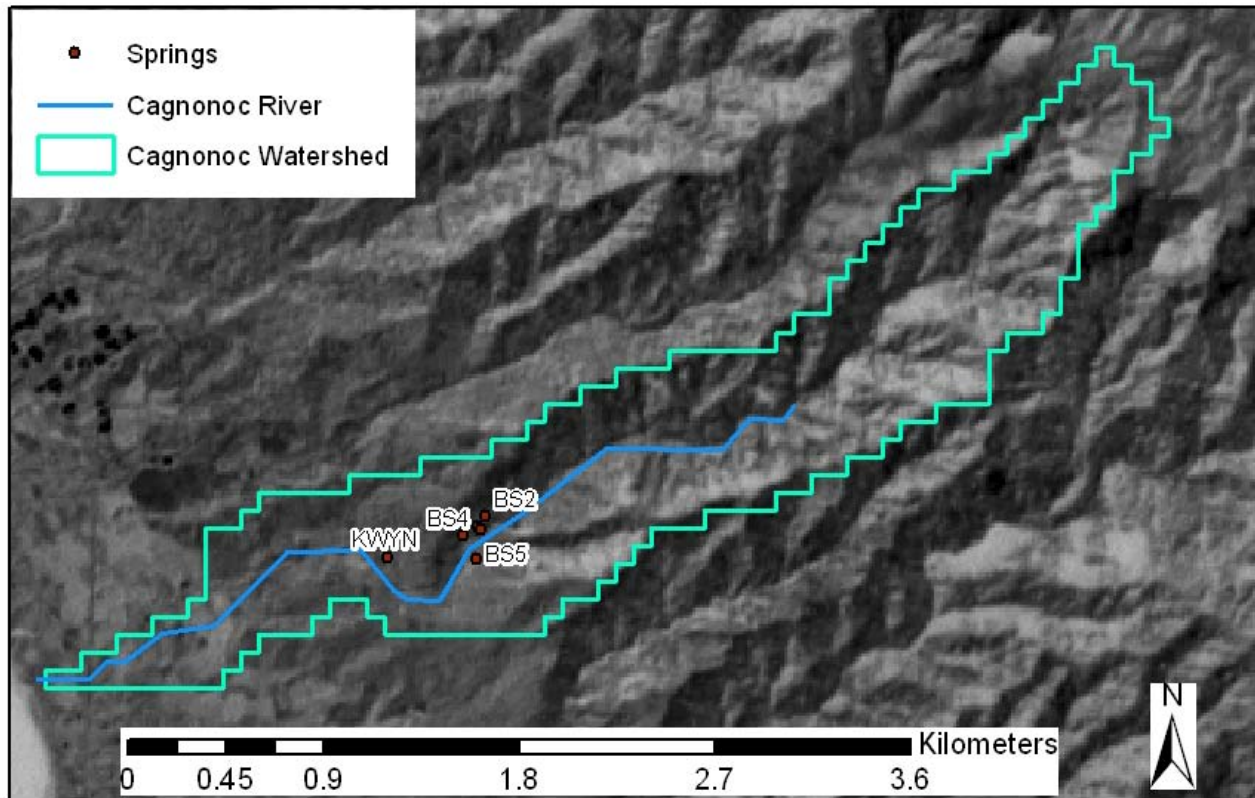


Figure 10. Map of Cagnonoc Watershed with Busay Springs 1-5 (BS#) and Kawayan Spring (KWYN) (Landsat image 30-m resolution Downloaded from Earth Resources Observation and Science Center (EROS) Produced by the U.S. Geological Survey)

1.1.5.2 Kawayan Spring

Kawayan Spring is located where the surface geology changes from the igneous rock of the mountain to a sandy-clay loam of the alluvial floor in the Cagnonoc Watershed (Figure 10). The topography also changes from steep to a more gentle slope where the rock changes to alluvium. A large embankment isolates the spring from the Cagnonoc River which is approximately 50 meters away. The spring is in a noticeable depression. A small creek of unknown origin is located approximately 100 meters to the north. Possible flow paths are similar to Busay Springs except the fissures or faults come in contact with a less porous alluvial floor creating a contact spring.

1.1.5.3 Hayas Springs

Formation of Hayas Springs is caused by the erosion of the valley slopes in the Ban-Utod Watershed. All five springs lie along the intersection between the mountain and the valley floor (Figure 11). Springs 1, 2, 3, and 4 are closely clustered on the South side of the valley while the Spring 5 is on the North side. The four springs are clustered less than ten meters apart and at the same elevation. Hayas 5 is about 500 meters farther up the valley. The

geology in the region indicates the springs have conditions similar to Kawayan Spring and Busay Springs, but the exact geological conditions of the springs were not identified due to alterations of the area during building of the spring boxes.

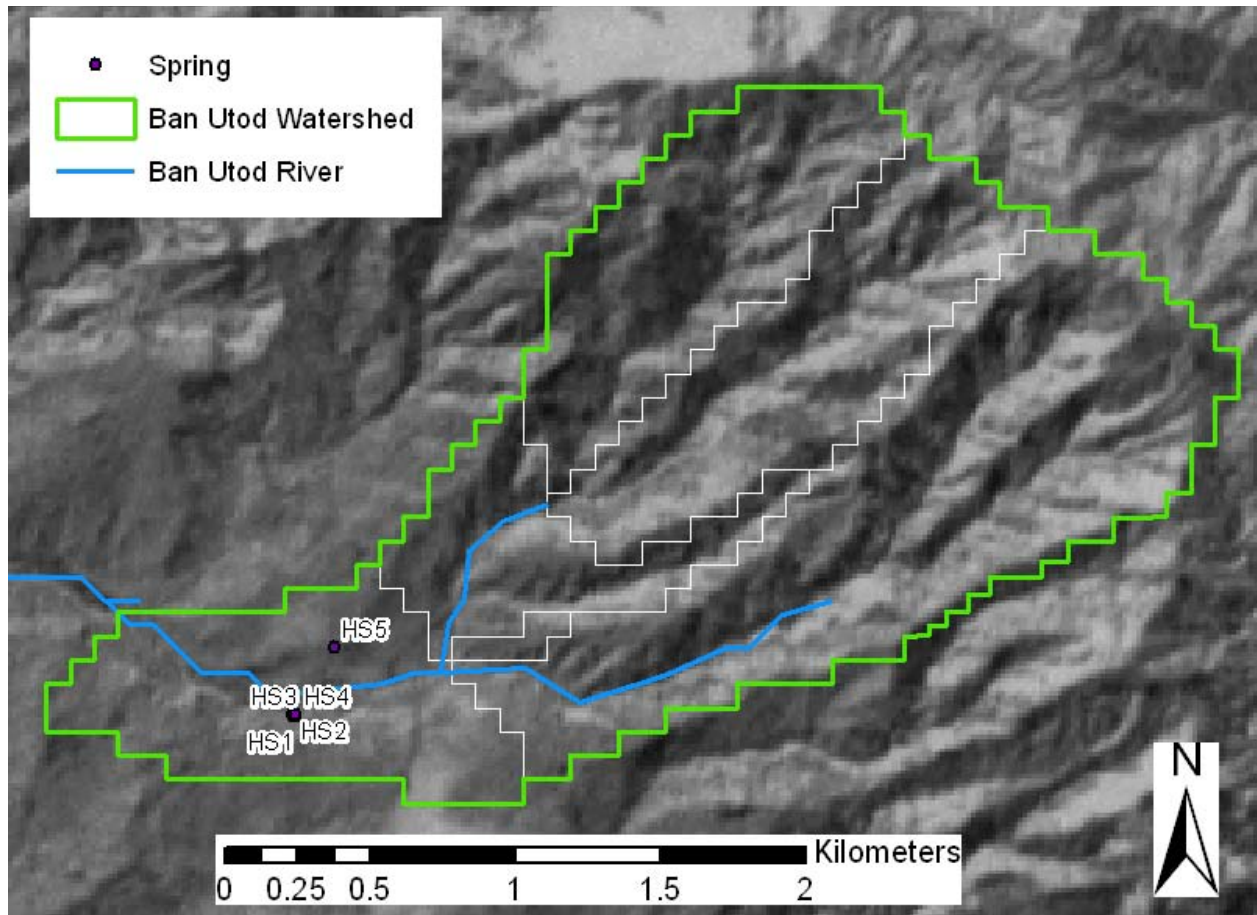


Figure 11. Map of Ban-Utod Watershed with Hayas Springs 1-5 (HS#) (Landsat image 30-m resolution Downloaded from Earth Resources Observation and Science Center (EROS) Produced by the U.S. Geological Survey)

2 Objectives

To develop a greater understanding of the spring hydrology that may improve water management plans, a conceptual model is needed that describes the various characteristics of spring-aquifer system for decision-making applications. Therefore, the main goal of this work is to develop appropriate conceptual models for the spring-aquifer systems. The objectives to achieve this goal are:

- A. Qualitatively determine the origin, aquifer type(s), connectivity, size, and a general description of the groundwater-flow regime.
- B. Quantitatively estimate the recharge areas, time lags, aquifer extents, and hydraulic conductivities of the aquifers.

The aquifer properties and flow characteristics provide information regarding the reliability of spring production in drought readiness and water allocation. Recharge area and flow characteristics address concerns regarding land-use management and spring protection.

3 Methods

To accomplish these objectives, several methods of analysis were used. Each method required a combination of field and laboratory data analysis. Listed in Figure 12 are characteristics of the spring-aquifer system and the analyses used in this study. Primary analysis allowed for direct qualitative and/or quantitative insight into the system. The supporting analysis either validated the primary analysis or served to narrow possible alternatives. Other methods to narrow alternatives and/or verify results were derived from basic fundamentals of hydrogeology: mass balance and Darcy's Law.

Origin/Flowpath

Primary – Isotope Analysis

Supporting – Water Chemistry & Time Series Analysis

Estimate Recharge Area

Primary –Water Balance (WB) Analysis

Recharge Location

Supporting – WB Analysis, Catchment Area Delineation

Aquifer Residence Time

Primary – Time Series Analysis

Supporting – Isotope Analysis

Aquifer Type

Supporting - Water Chemistry

Aquifer Size

Supporting – Time Series Analysis

Aquifer Hydraulic Connectivity

Supporting - Water Chemistry, Isotope Analysis, Time Series Analysis

Figure 12. Flow diagram for characterizing the spring-aquifer system with the type of analysis used in the investigation.

Oxygen 18 (O-18) and deuterium (D) isotopes are commonly used as tracers to study groundwater flow. The isotopic composition varies by the fractionation that occurs in natural processes, e.g., evaporation, condensation, mixing, etc. Studies have found that many of these processes such as evaporation and geothermal conduction create nearly linear relationships in isotopic compositions (Craig 1961, 1963, Dansgaard 1964). By understanding the isotopic compositions and the processes that create them, isotope analysis has become a valuable tool for studying groundwater origins and transport (Kendall and McDonnell 1998).

Many methods are available to study aquifer properties via spring flow data such as recession-flow analysis, frequency-domain analysis, spectral analysis, and correlation analysis (Manga 1999). However, most of these methods require large amounts of data and/or the appropriate hydrological timescale to be effective. For this study, correlation analysis of spring discharge and rainfall data is the most viable form of analysis due to limitations in the data's frequency and collection duration (span). This study followed the

methodology of Lee and Lee (2000), in which they used correlation analysis in studying aquifers for two years at time scales of hours, days, and months to quantify the time lag between the well water level fluctuations and rainfall history.

3.1 Field and Analytical Methods

Several field and analytical methods were employed for investigating the spring water origin, recharge area, and aquifer properties. Field methods involved regular recording of discharge rates and rainfall and collecting water samples for isotope and chemical analysis. All isotope and chemical analyses were conducted by certified analytical laboratories either in the Philippines or the United States.

Spring water discharge was monitored from one spring in each cluster. Measuring discharge required several techniques due to the unique design of each spring box and quantity of flow. The selection of springs monitored was based on accessibility. Busay 4 and Kawayan were measured daily either in the early morning or in the late afternoon (Figure 13 and Figure 14). Hayas 5 was measured two to three times a week at various daytime hours (Figure 15). Hayas 5 was measured by closing the discharge pipe in the pressure breaker box and then timing the fill rate. Busay 4 was measured with a bucket and timer. Kawayan was calculated by measuring the water height inside the spring box and correlated to estimated discharge rates.



Figure 13. Top view of Busay 4 spring box (Photo by author)



Figure 14. Side view of Kawayan spring box (Photo by author)



Figure 15. Side view of Hayas 5 spring box (Photo by author)

Rainfall was recorded at Busay springs two times each day using a ruler to measure depth in 2-inch diameter (nominal) tube. The gage was elevated off the ground and level in an open area that had no obstructions within 45 degrees from zenith (Dingman 2002). Monthly rainfall data for previous years (1988-2009) were obtained from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) Agromet Station, Visayas State University, Baybay City, Leyte. Besides rainfall data, monthly temperature and humidity data were also collected for the same period.

Physical and chemical parameters were analyzed at various dates throughout this study and combined with the water district records. Temperature and electrical conductivity were measured on site using a thermometer and electrical conductivity probe during the months of May, August, and December 2009. Basic water quality parameters (e.g.,

alkalinity, acidity, chloride, total hardness, pH, total solids, calcium, magnesium) have been laboratory tested every December since 2007 by the Department of Health at Eastern Visayas Regional Medical Center in Tacloban, Leyte. Additional testing for this study was conducted in September 2009 at the same laboratory in Tacloban. Sampling procedures followed laboratory protocols. Additional chloride tests were conducted for the May 2009 spring samples and March 2010 river samples by the Michigan Department of Community Health Upper Peninsula Laboratory in Houghton, Michigan. The holding time of the samples exceeded the recommended holding time according to Standard Methods for chloride testing. Nevertheless, the results are assumed valid due to the conservative nature of chloride. Full results are in Appendix B: Temperature & Chemical Data.

Samples were collected for analysis of O-18 and D isotopes in May 2009 and December 2009. These months represent the two months with the least and greatest average amount of rain, respectively. Samples from the nearby rivers were also collected in March 2010 to determine the river water origins (See Appendix C: River Isotope Analysis). Samples were collected in 60-mL bottles, sealed, and then analyzed using the cavity ring-down spectroscopy method at the Isolab at the University of Washington, Seattle.

3.2 Data Analysis

3.2.1 Origin of Spring Water

To determine if the spring water was of meteoric origin, the isotope data were compared to the Leyte Meteoric Water Line (LMWL, see Alvis-Isidro (1993)):

$$- \tag{1}$$

Deviations from the LMWL were investigated using chemical analysis, regional geography, and meteorological records.

3.2.2 Recharge Area Size

To estimate the recharge area, a water balance model was first developed for the spring-aquifer system. Then, various assumptions simplified the model and allowed the Thornthwaite-Type Monthly Water Balance Model (TWBM) to be incorporated. The TWBM was to model the various precipitation and evapotranspiration processes to estimate a “net” precipitation that infiltrates into the spring-aquifer system and exits through the springs discharge.

3.2.2.1 Water Balance Model

A simple water balance model for groundwater was adapted and modified to simulate hydrological processes over a given area and time (Dingman 2002):

Where,

Conceptually, water enters the area via precipitation or inflowing groundwater and exits via some combination of overland flow, groundwater seepage, spring discharge, and evapotranspiration. Storage can occur temporarily at various points throughout the watershed but this model only accounts for instantaneous changes in soil moisture up to the field capacity. Moisture beyond the field capacity is assumed to infiltrate and/or runoff and become spring discharge.

The model is subject to these assumptions:

- i. All water entering the groundwater originates solely from precipitation and therefore groundwater inflow G_{in} is negligible. This is confirmed with isotopic analysis.
- ii. Change in storage, S , is negligible as all quantities represent long term averages that complete or exceeds the annual meteorological cycle and therefore results in little storage (Dingman 2002).
- iii. Overland outflow, Q , is assumed negligible in the forest conditions as surface runoff is rare in mountain forests with deep soil/regolith mantles (Harden and Scruggs 2001). The forest soils of the region have been qualified as 4-m thick with high water-retention capacity (Asio 1996). Therefore, it is assumed that all rainfall, except for rain on the stream, infiltrates to the subsurface and travels along the subsurface before either joining a stream or the groundwater flow.
- iv. Groundwater outflow, G_{out} , that does not exit via the spring is likely present but no information is available to quantify the amount. This assumption of negligible G_{out} results in an underestimate of the spring recharge if the groundwater outflow and spring flow share the same recharge area. The recharge area estimated by this model is the theoretical minimum recharge area.

Incorporating these assumptions and adding a spatial dimension to the catchment area simplifies to the following model:

(3)

Where,

The precipitation minus the evapotranspiration can be thought of as the net precipitation.

3.2.2.2 Application of the Thornthwaite-Type Monthly Water-Balance Model

The TWBM calculated the net precipitation. This model was most appropriate for this study given the available meteorological data. This lumped conceptual model uses the temperature-based Hamon model to calculate evapotranspiration and soil-water storage capacity to calculate soil moisture. Model parameters include: latitude, soil field capacity (θ_{fc}), root zone depth (Z_{rz}), monthly precipitation (), and average monthly temperature (). Figure 16 shows that evapotranspiration and soil moisture are relatively constant in comparison to the monthly precipitation. The annual Actual Evapotranspiration (AET) was nearly identical to the annual Potential Evapotranspiration (PET) value (<1% difference).

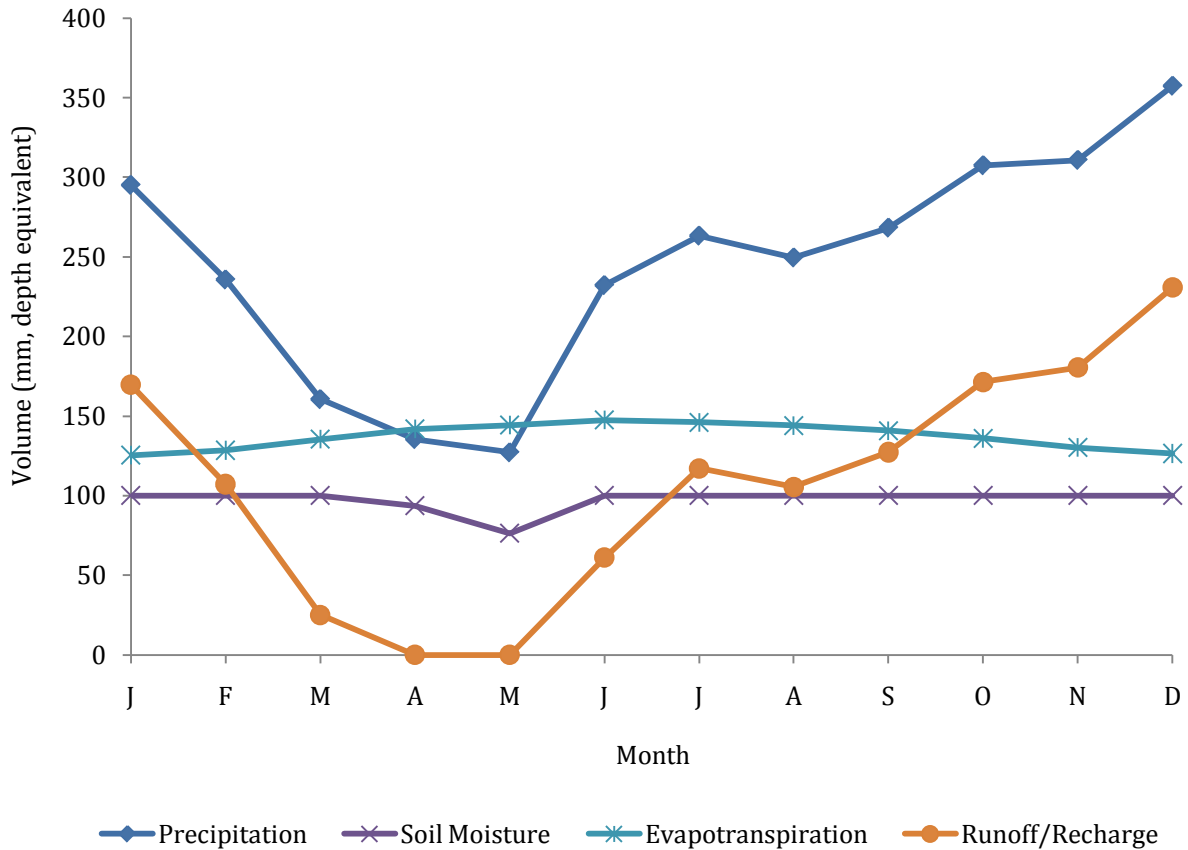


Figure 16. TWBM of average monthly rainfall and average monthly temperature

Potential evapotranspiration models¹ are not ideal for forest hydrology and ignore interception loss (i.e., precipitation retained in the canopy). Interception losses can range from 10% to 40% in forested areas depending on the plant community and can skew the empirical PET models because the interception loss is affected by evaporation at a faster rate than transpiration (Dingman 2002). The Hamon model has performed best in estimating annual runoff for 120 broadleaf forests in the USA, with the least bias and least mean absolute error over nine different models (Vörösmarty et al. 1998). Therefore, this model should most accurately estimate the PET with the given data constraints. Estimates for interception loss in tropical forests are 20% of the gross precipitation (Dingman 2002).

Soil moisture has little impact on recharge since the monthly precipitation is so high that soil moisture remains at capacity throughout most of the year. Table 2 shows the sensitivity to change in soil moisture parameter values.

¹ The definition of PET is somewhat ambiguous in defining the type of vegetation. Commonly vegetation is refer to “a short crop that covers the whole ground” (Dingman 2002).

Table 2 Sensitivity Test of TWBM

Soil Moisture Parameters	Rainfall (mm)	PET (mm)	AET (mm)	Recharge (mm)	Change in Recharge
Average values ($\theta_{fc}=0.2$, $Z_{rz}=500$ mm)	3000	1650	1650	1300	0%
High values ($\theta_{fc}=0.3$, $Z_{rz}=1000$ mm)	3000	1650	1650	1290	-0.2%
Low values ($\theta_{fc}=0.1$, $Z_{rz}=200$ mm)	3000	1650	1640	1300	0.7%

3.2.3 Recharge Location

Since determining the recharge location was outside the capabilities of this study, narrowing of locations for the recharge involved comparing the possible catchment areas to the TWBM estimates. The most likely catchment area extended upslope of the watershed where the spring is located. The assumption is that groundwater flow mimics the topography and does not cross watershed or valley floor boundaries. TWBM estimates were also compared to the total area of the watershed.

3.2.3.1 Delineating the Catchment Area

Delineation of spring catchment area was based on the “New Hampshire” methods (US Department of Agriculture [USDA] 1991). The delineation procedure was slightly modified for the springs due to the close clustering of the springs and/or the contour lines running parallel near the spring (this created no catchment area). Delineation began slightly downhill of the spring and then followed parallel to the contour lines until reaching the watershed boundary or the valley floor. Then, the delineation followed perpendicular to the contour lines until enclosing the area. Delineations were done in clockwise and counterclockwise directions with the larger area being selected as the catchment area. The delineations created catchment areas that followed along the hillside of the watershed. Busay 1-4 with Kawayan and Hayas 1-4 were each clustered as single catchment areas.

3.2.4 Time Lag

The plausible time lags between rainfall and spring discharge were identified using correlation analysis of rainfall data and spring discharge data. Analysis began with the daily rainfall and discharge data. Once no strong patterns were identified, monthly rainfall and discharge rates were analyzed. The time lag of Busay 4 was verified by inspecting the

historic weather conditions of the estimated time lag for typhoons that explain observed anomalies in the isotope data.

The rainfall data was first processed using cross-correlation analysis (CCA) to recognize the strength of cyclical/seasonal rainfall patterns. In areas where seasonal rainfall patterns are consistent, monthly rainfall data correlates strongly with the average monthly rainfall. However, in areas with erratic precipitation, correlation of monthly rainfall data with the average is poor. This information identifies whether the apparent rainfall-induced spring discharge pattern is unique to inputs of rainfall data. Since no strong cyclical patterns existed, CCA was conducted to identify possible time lags between rainfall and spring discharge. The analysis spanned five years from 2009 to 2004, since seasonal fluctuations of isotopes are only detectable for a maximum of four years (Zuber and Maloszewski 2000).

In regular correlation analysis, the correlation coefficient is the strength of the linear relationship between two quantitative sets of variables (Freund and Wilson 2003). Cross-correlation analysis quantifies the interrelationship between the input and output series at different time lags by shifting the input series chronologically (Lee and Lee 2000). The linear correlation, representing the interrelationship strength, then oscillates between +1 and -1 with the closest correlation to +1 signifying the strongest relationship between input and output.

The multiple lag times of Busay 4 were investigated for the occurrence of typhoons that corresponded to the May 2009 anomalous isotopic composition. The timing of the typhoon is consistent with the plausible time lag and established the time as an approximate residence time.

3.2.5 Aquifer Properties: Type, Connectivity, Size

The aquifer properties were explored indirectly using water chemistry data, time-series analysis, and isotope analysis and quantified using the fundamental hydrogeology principles: mass balance and Darcy's Law.

Aquifer type was assumed from the geological description of the area and then confirmed by water chemistry data. Electrical conductivity (EC), chloride, magnesium, and calcium compared with expected values for igneous aquifers.

Aquifer connectivity was studied by comparing temperature, EC, chloride, magnesium, calcium, and water isotope values. Similar values indicate the same aquifer, different water chemistry values indicate different aquifers, and different isotope values but similar water chemistry values require further inspection (Mazor 1991).

Characterizing the aquifer size involved statistical analysis of the 13 -months of discharge data. The mean, coefficient of variation (CV) of discharge, and minimum discharge rate are

characteristics of the aquifer's size and capacity. An example is that a high CV and a low minimum discharge indicate a relatively small aquifer which is highly affected by rainfall events. A high CV is indicative of a larger aquifer.

Ranges in aquifer volume, aquifer thickness, and hydraulic conductivity were narrowed by using mass balance and Darcy's Law. The mean aquifer size and aquifer thickness was calculated using mass balance. The plausible time lag, T_L , represented an approximate water residence time, T_{age} . The relationship between the aquifer dimensions and the approximate residence time is expressed as:

(4)

Where,

Mean discharge rates, Q , were from this study or Baybay City Water District estimates in 2005. The Baybay City Water District estimates were single data points and had a difference of 2-3 L/s when compared to the results of this study for Hayas 5 and Kawayan. Reported range in porosities, n , for basalts were from Dingman (2002). To estimate aquifer thickness, the recharge areas were assumed to be approximately proportional in size to the area of the aquifer and were taken from the TWBM.

Estimates in hydraulic conductivity were calculated using Darcy's Law. The relationship between the residence time and characteristics of the aquifer using Darcy's Law was:

(5)

Where,

[L/T]

[L/L]

Assuming the lateral extent of the aquifer mimics the topographic watershed boundary, the average length of flow path, L , and hydraulic gradient, i , were estimated from the characteristics of the watershed. Calculations of the hydraulic gradient did not include the top 10% of the watersheds since the slope gradients increases dramatically (Figure 4). Hydraulic conductivity values were then compared to typical values (Dingman 2002).

3.2.6 Characteristics of Groundwater Flow

Groundwater flow characteristics were conceptualized by comparing the time series of each monthly unit discharge² to the rainfall pattern of the purposed time lag and its expected recharge calculated by the TWBM. Time series plots allowed visual assessments of the monthly spring discharge response to the corresponding rainfall/recharge inputs. The results were compared to aquifer properties.

The 2009 $\delta\text{O-18}$ isotope data was also compared to the corresponding recharge in the time series plot. This information combined with the general flow characteristics provided insight into the possibility of multiple flow components, i.e. base flow and shallow groundwater flow (interflow). Base flow was considered present for springs with relatively constant discharge. Therefore, if no recharge had occurred during the previous months according to the TWBM then the isotope sample was a representation of the base flow. If recharge had occurred, then the isotope sample represented a mixture of base flow and interflow. This is based on hydrograph separation studies that found monthly $\delta\text{O-18}$ content of the shallow-groundwater flow to fluctuate, while the monthly $\delta\text{O-18}$ content of the base flow remained constant (Uhlenbrook et al. 2002).

4 Results and Discussion

4.1 Origins

The isotope ratio of O-18: D indicates that the waters from Hayas and Kawayan are meteoric in origin. Hayas and Kawayan results closely follow the Leyte Meteoric Water Line (LMWL) in May (Figure 17) and December (Figure 18). A shift occurs in isotope compositions between the months indicating possible seasonal variations in precipitation (Kendall and McDonnell 1998). The significance of the shift is debatable because of the standard deviations for May results are high (Table 3). The standard deviations are from the laboratory analysis.

² Monthly unit discharge was computed by dividing the average monthly discharge rate by the TWBM recharge area. The TWBM recharge areas were calculated using rainfall and temperature data of the proposed time lag.

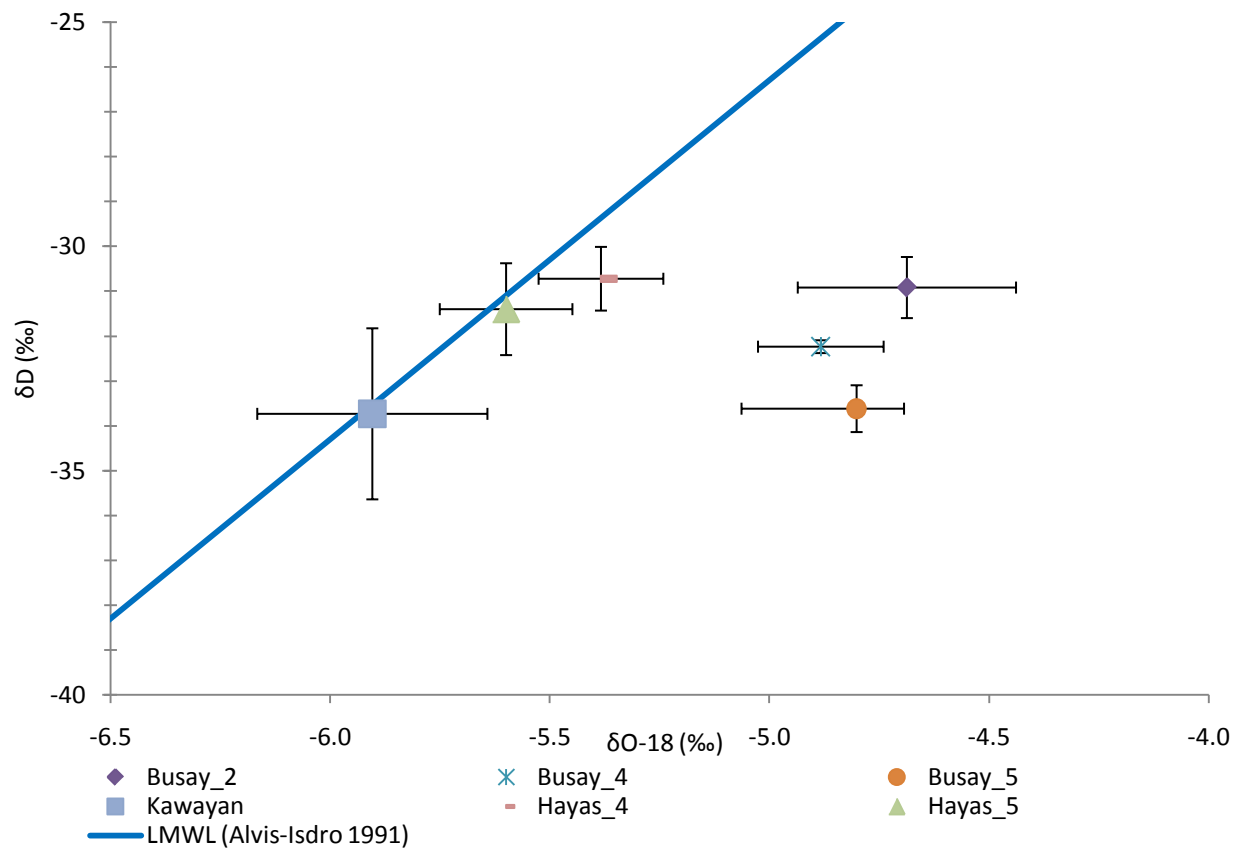


Figure 17. May 2009 isotopic compositions for springs. Vertical and horizontal bars represent standard deviations of δD and $\delta O-18$ values from laboratory analysis, respectively.

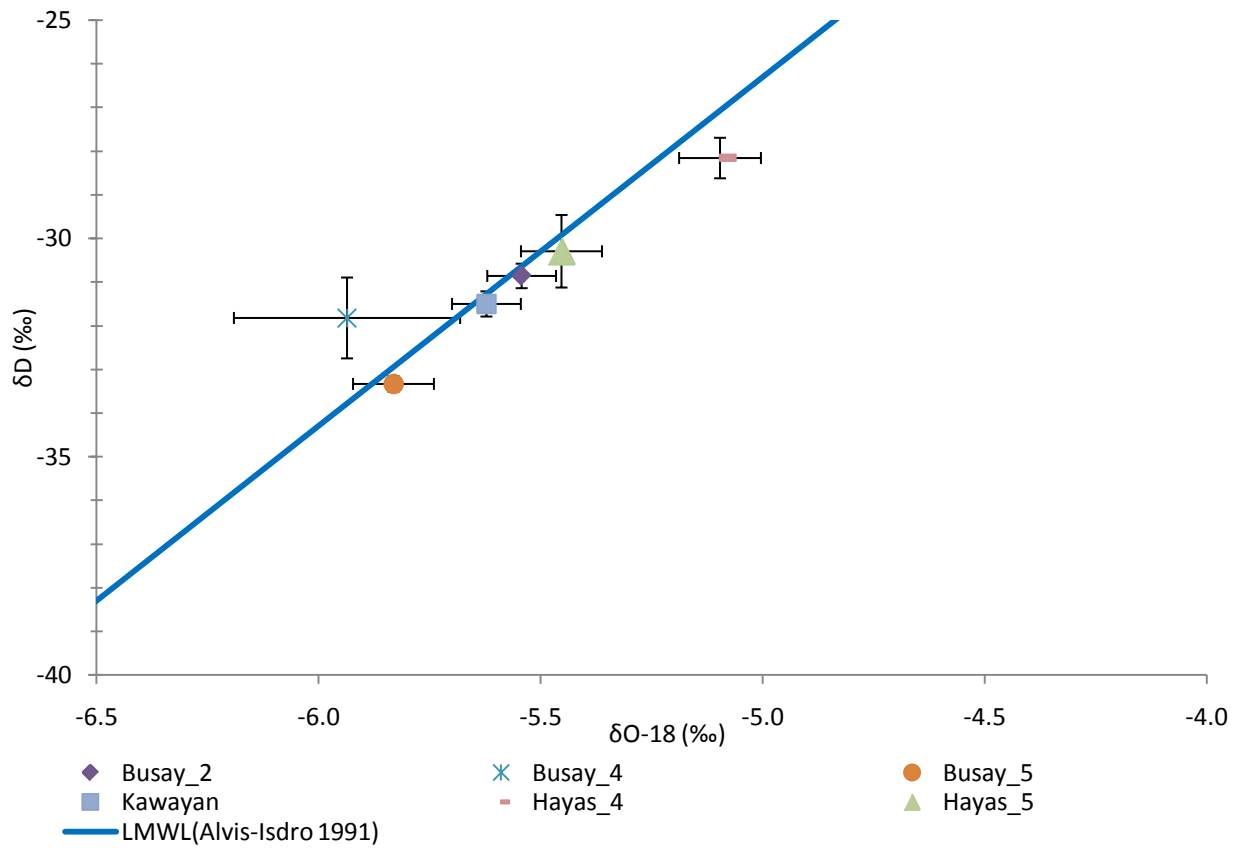


Figure 18. December 2009 isotopic compositions for springs. Vertical and horizontal bars represent standard deviations of δD and $\delta O-18$ values from laboratory analysis, respectively.

Table 3. Comparison of Isotopic Samples (May 2009, Dec. 2009).

Spring	Month	$\delta\text{O-18}$ (‰)	Std Dev δO18	δD (‰)	Std Dev δD
Busay 2	May	-4.69	0.25	-30.92	0.68
Busay 2	December	-5.54	0.08	-30.86	0.28
Busay 4	May	-4.88	0.14	-32.24	0.66
Busay 4	December	-5.94	0.25	-31.87	0.93
Busay 5	May	-4.80	0.11	-33.62	0.52
Busay 5	December	-5.83	0.09	-33.33	0.18
Kawayan	May	-5.90	0.26	-33.73	1.91
Kawayan	December	-5.62	0.08	-31.50	0.29
Hayas 4	May	-5.38	0.14	-30.72	0.71
Hayas 4	December	-5.10	0.09	-28.16	0.46
Hayas 5	May	-5.60	0.15	-31.40	1.02
Hayas 5	December	-5.45	0.09	-30.29	0.83

The origins of the Busay spring water are more uncertain due to the isotopic results in May and require additional information. While the December results indicate meteoric origins, May isotope results deviate significantly from the LWML. This deviation in May alludes to four possible causes: (1) evaporation, (2) mixing and dispersion with a different water source, (3) typhoon, or (4) error (Lawrence et al. 1998, Kendall and McDonnell 1998). Evaporation seems somewhat unlikely because there are no sources of lakes or rivers with long surface exposure times existing in this mountain region. Studies have shown that transpiration and evaporation occurs if subsurface flow is shallow and in much drier environments (Kendall and McDonnell 1998). Mixing with an alternative water source is possible given the geothermal activity of the region. However, studies on magmatic waters also possess properties such as high temperature (>45 °C) and /or high dissolved salts, such as chloride (>2000 ppm) (Alvis-Isidro 1993, Bryan 1981). Physical and chemical analysis of water samples detected neither high temperature nor high Cl⁻ (See Appendix B: Temperature & Chemical Data). Typhoons are frequent to the area. Various studies have found that the isotopic compositions of precipitation from typhoons/hurricanes deviate significantly from the MWL (Lawrence et al. 1998, Ohsawa and Yusa 2000). Lawrence et al. (1998) has studied multiple hurricanes and found the isotopic composition varies spatially throughout the typhoon/hurricane radius of influence and by weather system. Error during sample collection or storage seems unlikely as all samples were collected and stored in the same manner. Samples bottles were sealed and double -bagged to prevent evaporation. The other samples showed no evaporation in analysis.

4.2 Recharge Area Comparison

Catchment delineations of springs are given in Figure 19 and Figure 20. All catchment areas, except for the catchment area of Busay 5, extend the entire length of the upper watershed. Busay 5 is an exception because of a distinct valley to the east of the spring. (For catchment delineations of entire watershed upslope of springs, see Appendix D: Delineation of Watersheds Upslope of Springs)

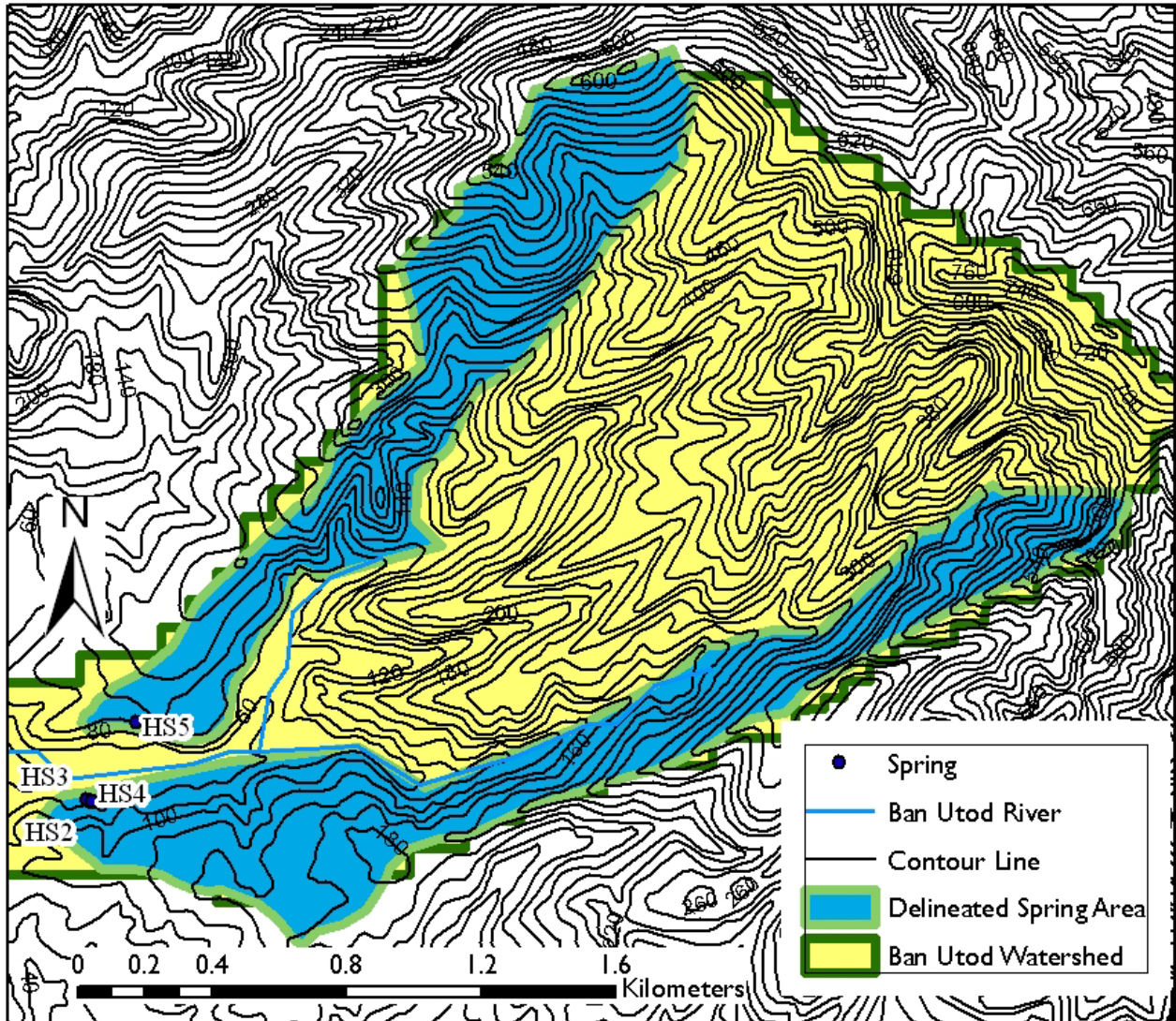


Figure 19 Delineation of catchment areas extending the length of the watershed for Hayas Springs 1-5 (HS#) (image exported from ArcGIS 9).

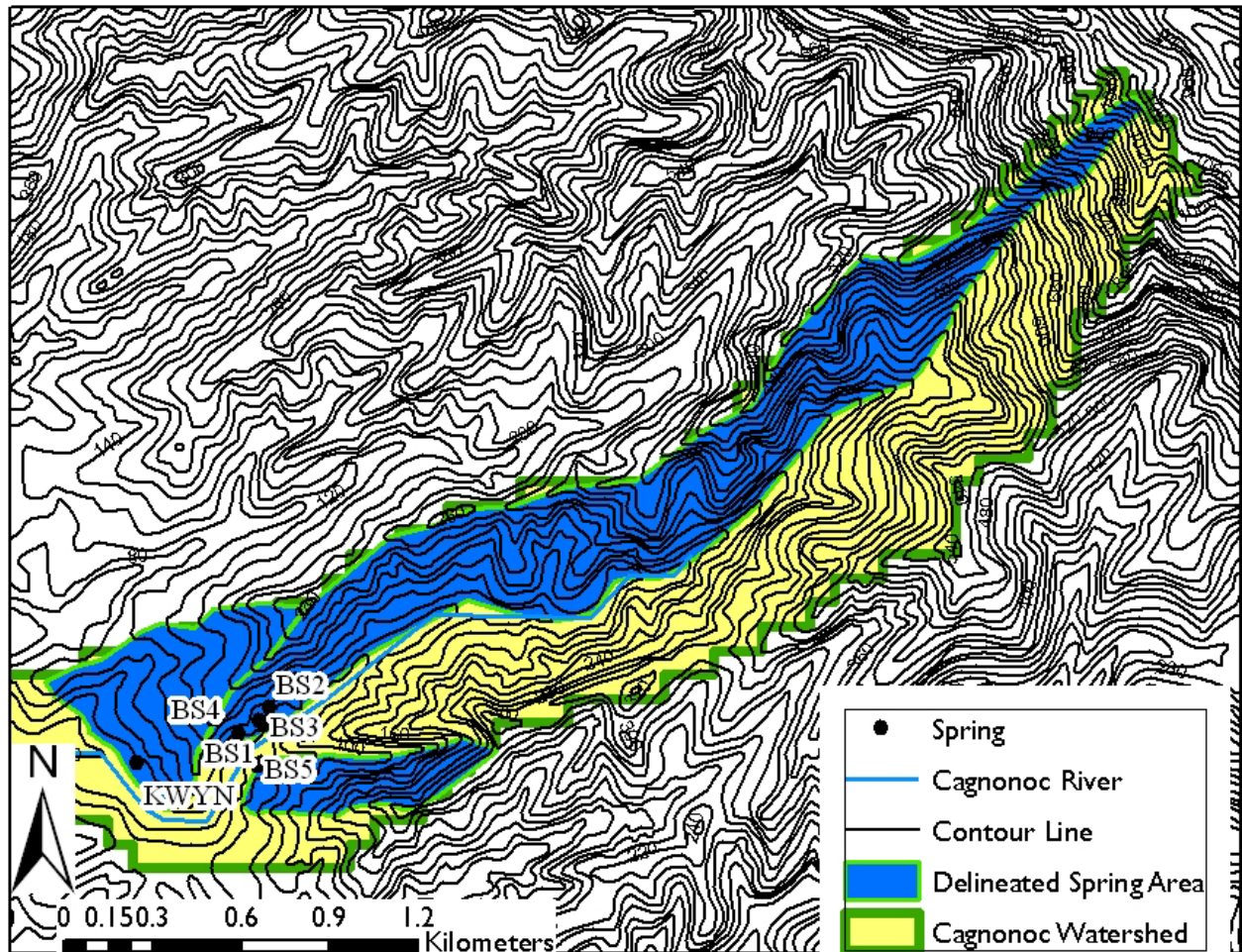


Figure 20 Delineation of catchment areas extending the length of the watershed for Busay Springs 1-5 (BS#) and Kawayan Spring (KWYN) (image exported from ArcGIS 9)

The areas of the catchment delineations exceed the TWBM recharge area estimates for Hayas 1-4 (81%) and Hayas 5 (230%) but are less than the TWBM estimates for Busay 1-4 and Kawayan (-14%) and Busay 5 (-18%) (Table 4). In comparison of the TWBM recharge area to the total watershed area, Busay and Kawayan springs require 45% of the Cagnonoc Watershed to maintain perennial flow and Hayas springs require 15% of the Ban-Utod Watershed.

Table 4 Comparison of Delineated Catchment Area to TWBM Estimates.

Spring	Estimated Discharge Rate (L/s)	Delineated Area (ha)	TWBM Area Estimates (ha)	Difference in Areas (Delineated - TWBM)	Difference from TWBM (%)
Busay 1,2,3,4 & Kawayan	58	130	151	-21	-14%
Busay 5	7	14	17	-3	-18%
Hayas 1,2,3,4	20	87	48	39	81%
Hayas 5	10	79	24	55	229%

Results from the TWBM represent the minimum recharge area needed for the springs. As previously discussed the Methods section, underestimation in size is caused by the unknown amount of groundwater outflow bypassing the springs.

4.3 Time Lag

No relationship between rain events and daily discharge was seen in the daily spring discharge and rainfall patterns (See Appendix E: Plot of Daily Rainfall and Spring Discharge (Nov 2008-Nov 2009).) nor did CCA of daily rainfall to discharge uncover correlations (Busay 4 $R^2=0.013$, Kawayan $R^2=0.18$, Hayas 5 $R^2=0.071$). Kawayan shows possible trends between rainfall and discharge but explanations for events such as the dramatic decrease in discharge in February and August remain unclear. Busay 4 shows little response to the rainfall input throughout the year but fluctuates daily. The Hayas 5 discharge fluctuates daily during the initial months as its flow increases, then is relatively consistent from March 2009 until September 2009, and then fluctuates again as the daily discharge decreases.

Once no patterns were found in the daily discharge analysis, monthly analysis began by analyzing rainfall patterns. In analyzing cyclical patterns of rainfall, the cross-correlation of monthly rainfall data to average monthly rainfall shows no obvious annual cyclical pattern (See Appendix G: Cross-correlation of Average Monthly Rainfall (1988-2009) to Monthly Rainfall from 2004 to 2009.). As Figure 21 shows, some years of rainfall patterns, such as 2007, strongly correlate to the average monthly rainfall but others show zero or negative correlation.

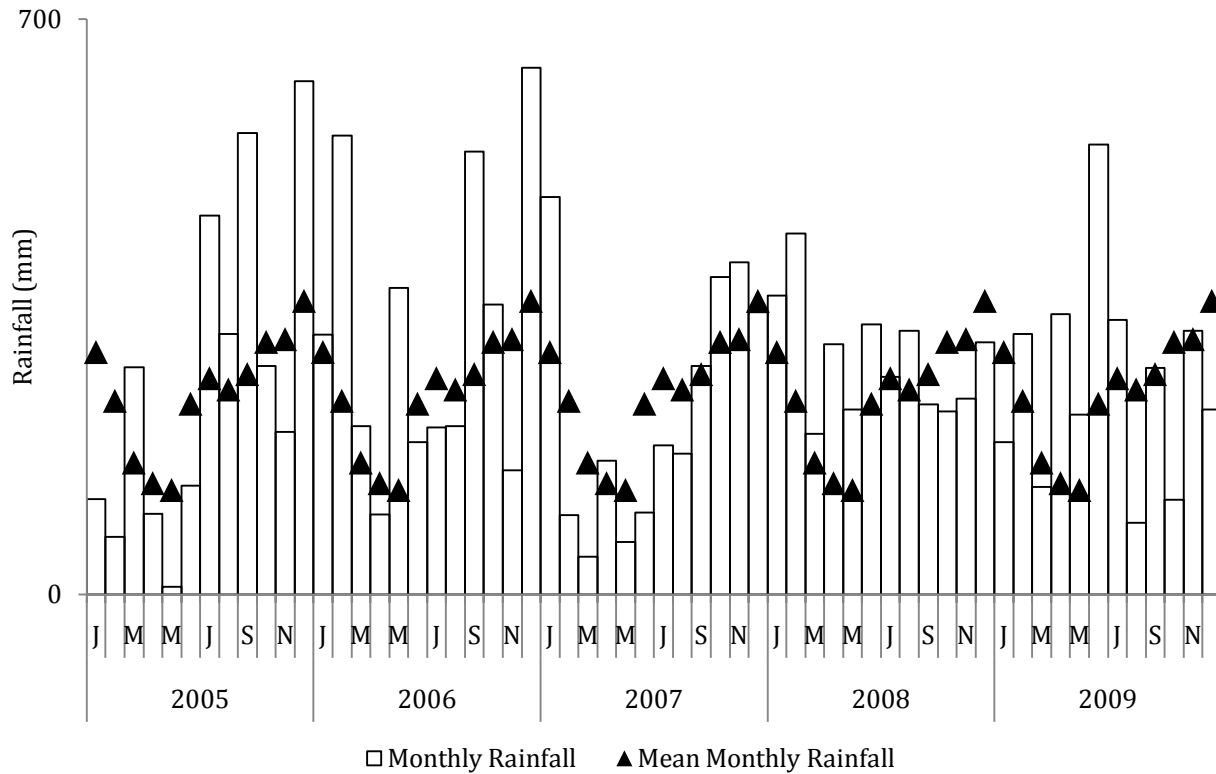


Figure 21. Comparison of mean monthly rainfall pattern to monthly rainfall pattern (2005-2009).

With the absence of a cyclical pattern in five years of monthly rainfall data, the thirteen months of average monthly discharge data were cross-correlated to the five years of rainfall data (Figure 22, Figure 23, and Figure 24). Correlations are low or negative for most time lags except for a few months with correlation coefficients above 0.41 ($p < 0.01$). Estimated time lags based on the strongest correlation would be 16 months (1.3 years) for Hayas 5, 24 months (2 years) for Kawayan, and 29 months (2.4 years) for Busay 4 (See the regression analysis in Appendix H: Scatter Plots of Most Plausible Time Lags). These correlations are reasonable considering other processes such as evapotranspiration, mixing, and infiltration, which are neglected in this method. Also, in comparison to other studies by Lee and Lee (2000), Manga (1999), and Angelini (1997), these correlations are within reasonable values. However, uncertainty arises in the validity of time lags as Hayas 5 has several possible time lags that exceed correlations of 0.41 (Hayas 5 $T_L=17, 18$ months).

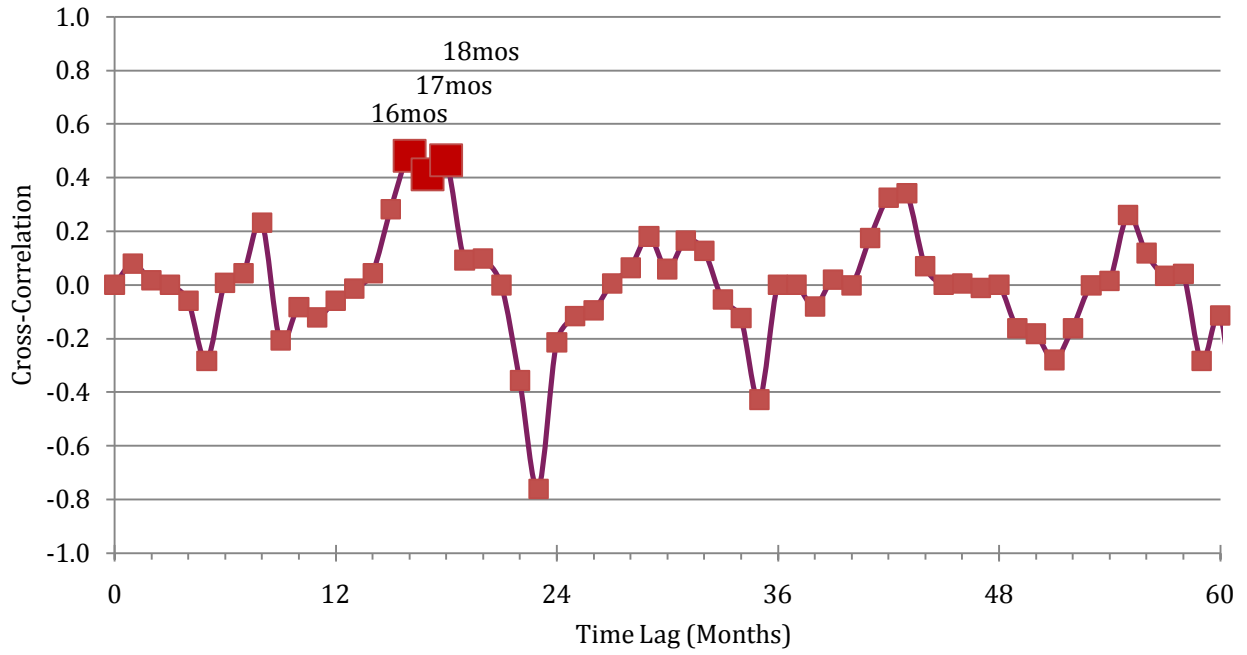


Figure 22. Cross-correlation function of monthly discharge to monthly rainfall (Hayas 5).

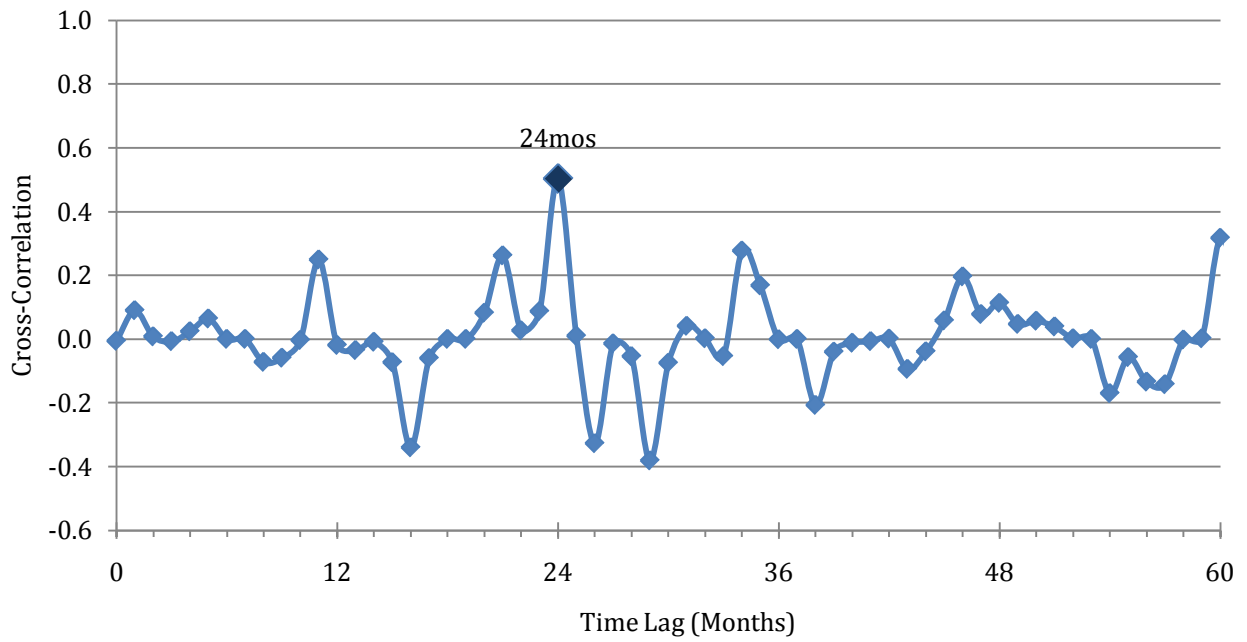


Figure 23. Cross-correlation function of monthly discharge to monthly rainfall (Kawayan).

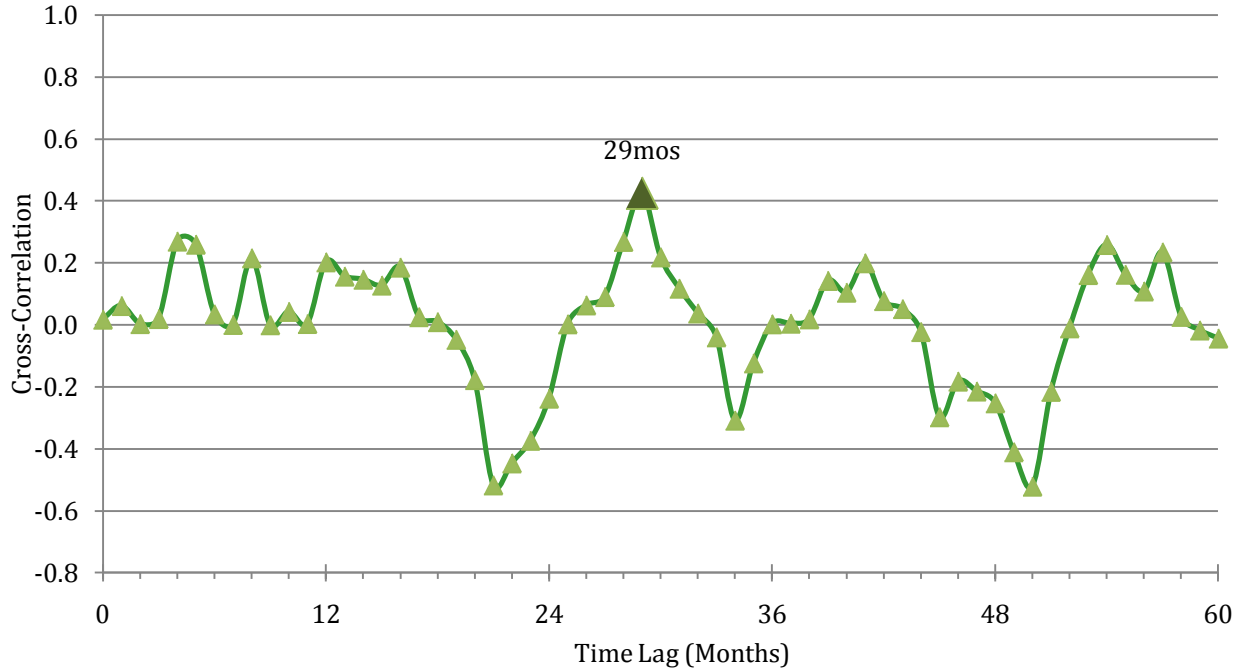


Figure 24. Cross-correlation function of monthly discharge rates to monthly rainfall (Busay 4).

Since plausible time lags for Hayas 5 were in consecutive months ($T_L=16-18$ months), the time lag was analyzed at 16 months only. The Busay 4 time lag ($T_L=29$ months) was investigated for typhoons hitting Leyte that could explain the May 2009 isotope composition. On 9 December 2006, Typhoon Utor had made landfall in Leyte causing rainfall that explains the shift in isotope composition (Figure 25) (Wikimedia Commons 2006).

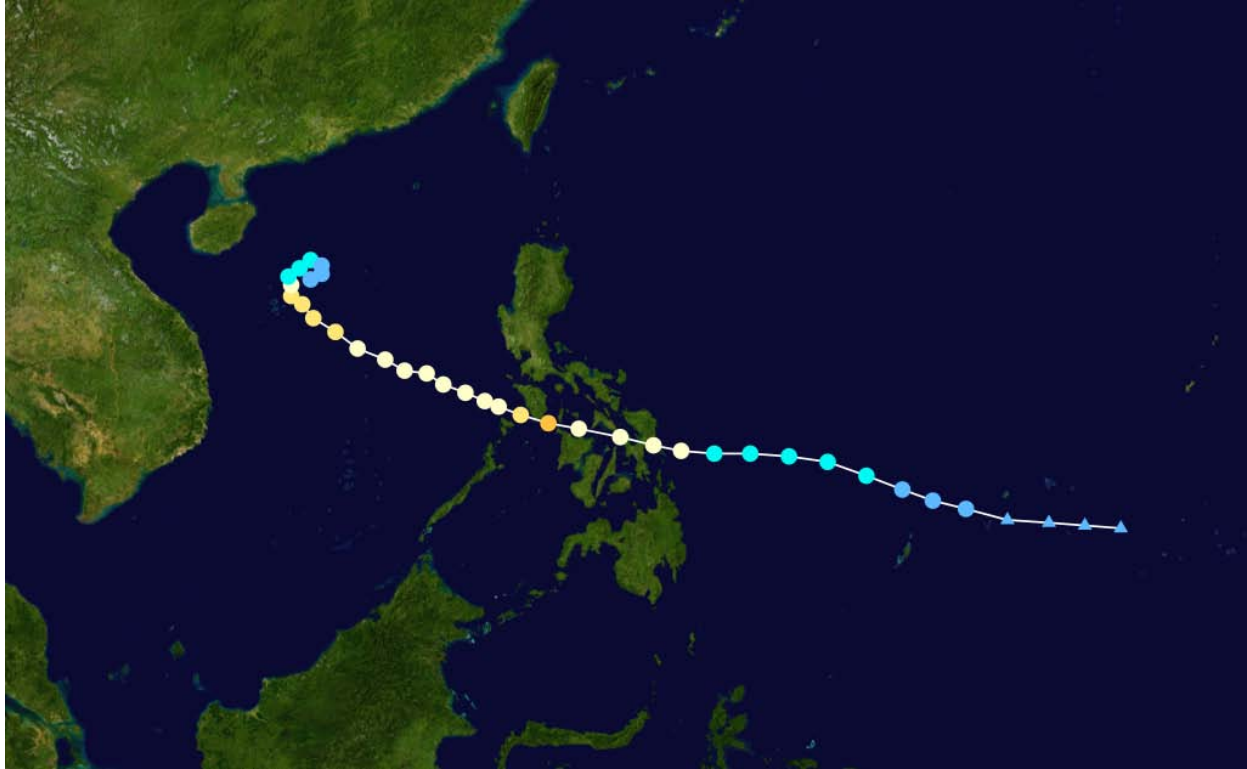


Figure 25. Path of Typhoon Utor from 2-14 December 2009. (File from Wikimedia Commons 2006)

4.4 Aquifer Properties

4.4.1 Aquifer Type

Electrical conductivity (EC), chloride, calcium, and magnesium levels all compare to expected results for water equilibrated in igneous rocks. Electrical conductivity and ion concentrations are low throughout, as exhibited in Table 5, Figure 26, Figure 27, and Figure 28. The low EC and chloride levels indicate water from precipitation that has little dissolution of the parent rock material. This is common in igneous -rock aquifers (Ward and Robinson 2000).

Table 5. Electrical Conductivity (μS) Measurements of Springs

	Busay 2	Busay 4	Busay 5	Kawayan	Cagnonoc River	Hayas 4	Hayas 5	Ban-Utod River
May-2009	95	95	126	98	111	151	152	99
Aug-2009	95	98	124	99	115	148	134	109
Dec-2009	95	96	126	97	82	154	139	100

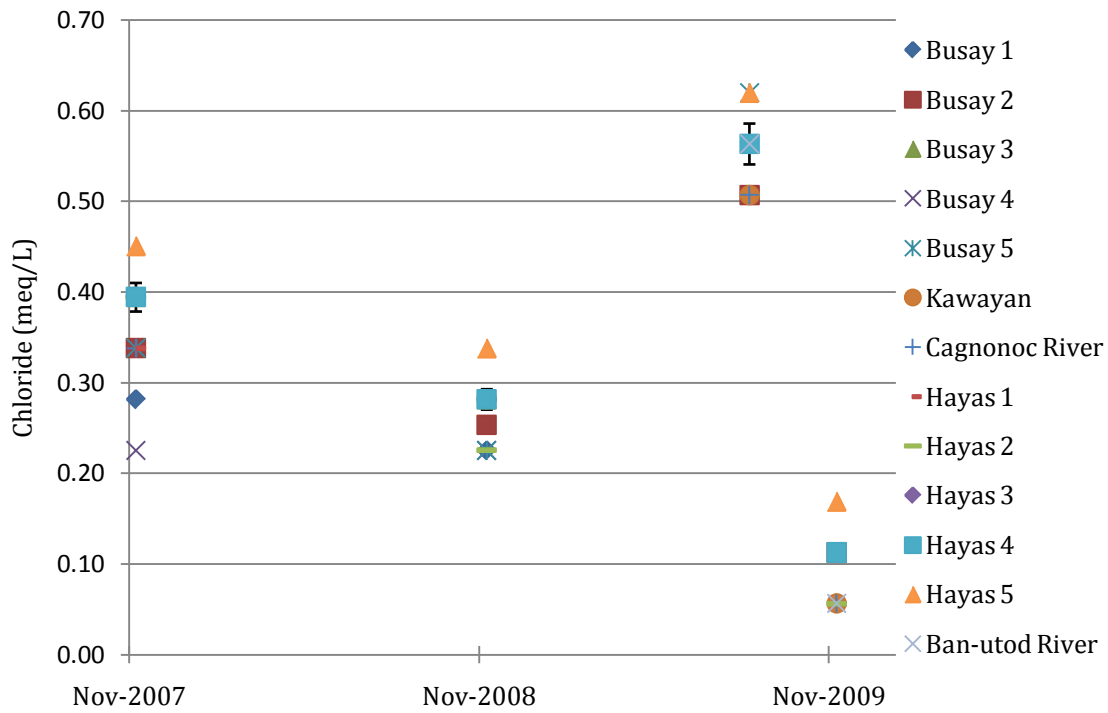


Figure 26. Time series of chloride levels in spring and river water samples.

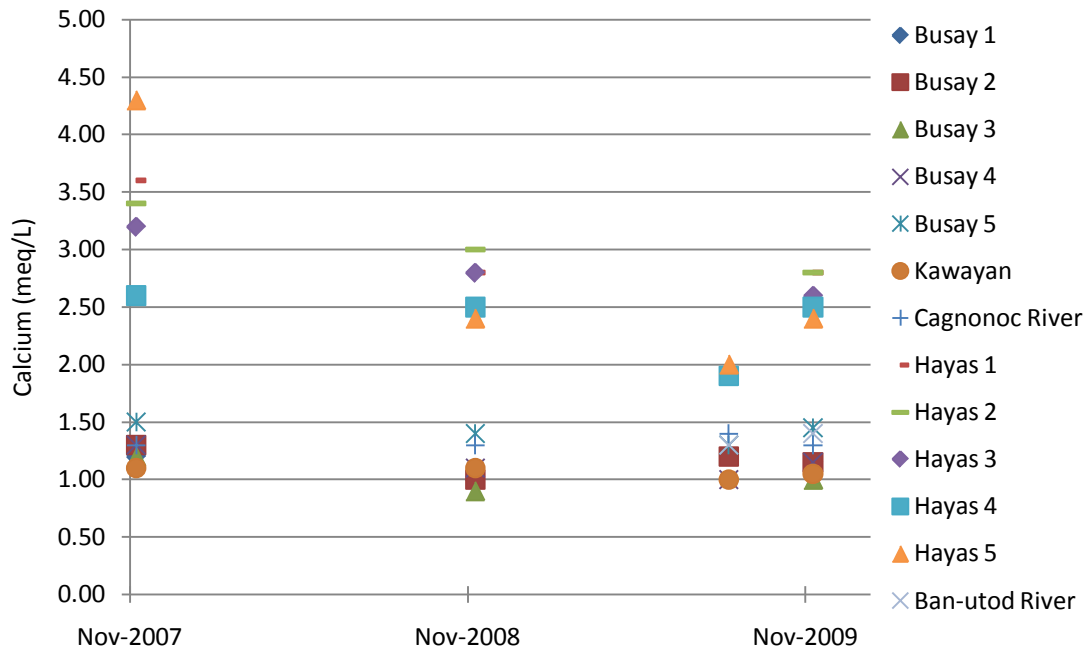


Figure 27. Time series of calcium levels in spring and river water samples.

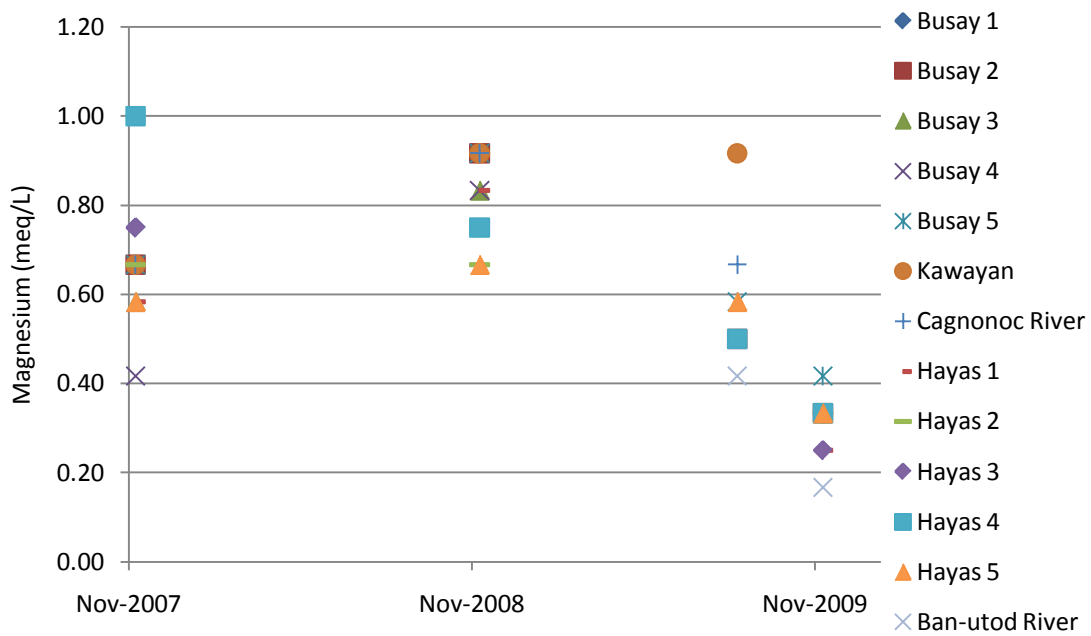


Figure 28. Time series of magnesium levels in spring and river water samples.

4.4.2 Hydraulic Connectivity

Hayas, Busay, and Kawayan springs are assumed to be associated with different aquifers. The EC values (Table 5) and calcium concentration levels (Figure 27) for Hayas Springs and Busay Springs/Kawayan fluctuate at consistent values between each spring cluster throughout the three years. Kawayan and Busay Springs may originate from the same aquifer since the springs are in the same watershed. However, the estimated time lags are inconsistent with the spring locations, which points to the springs being from separate aquifer sources. Kawayan Spring is approximately 500 meters downhill from Busay Springs, and therefore Kawayan Spring should have a longer time lag if part of the same aquifer as Busay Springs.

The Busay springs seem to be part of the same aquifer, as isotope and chemistry data fluctuate identically throughout the years (See Figure 17 & Figure 18 for isotope data, Figure 26 Figure 27 & Figure 28 for chemical data). Connectivity between Hayas Springs 1 - 4 is more certain because the springs are just a few meters from each other and their similar water chemistry data. The hydraulic connectivity of Hayas 5 to the rest of the Hayas Springs is uncertain because the isotope compositions varied by at least 0.35‰ during both sampling periods (Table 3).

4.4.3 Aquifer Size

A statistical breakdown of the spring discharge data is summarized in Table 6.

Table 6. Statistical Summary of Discharge during Study (Nov 2008-Nov 2009).

	Busay 4	Kawayan	Hayas 5
Average Discharge (L/s)	0.73	12.03	10.12
Standard Deviation	0.09	0.65	2.82
Coefficient of Variation	12%	5%	28%
Maximum Discharge (L/s)	1.00	13.18	16.54
Minimum Discharge (L/s)	0.49	10.23	2.80
Number of data points	322	315	100

Kawayan exhibits relatively constant flow (average of 12.03 L/s) with a 5% CV, probably signifying a large aquifer supplying the spring flow. Hayas 5 averages 10.12 L/s but varies at a 28% CV and a minimum discharge of 2.8 L/s, both indicating a smaller, highly responsive aquifer to rainfall variations. The Busay 4 aquifer size is moderate in comparison to spring discharge with 12% CV. The 12% CV of discharge is significant since the combined Busay Springs discharge is approximately 58 L/s.

Table 7 shows estimates of aquifer volume and aquifer thickness for the Busay Springs, Kawayan, and Hayas 5. Hayas Springs are not estimated due to uncertainty in the time lag of these springs.

Table 7. Volume and Aquifer Thickness Estimates

Porosity*	Mean Volume (ha-m)			Aquifer Thickness (m)		
	0.03	0.17	0.35	0.03	0.17	.35
Busay Springs	1453	256	125	10.46	1.85	0.90
Kawayan	145	26	12	8.54	1.51	0.73
Hayas 5	138	24	12	5.76	1.02	0.49
From Dingman 2002*						

Hydraulic conductivity estimates using Darcy's Law are calculated below to check the practicality of the results (Table 8). All hydraulic conductivities are within the expected range for highly fractured basalts (Dingman 2002). Average slope and length of flow path are estimated from the watershed geomorphology. Time lags/residence times are from this study.

Table 8. Range of Hydraulic Conductivities

Spring	Hydraulic Conductivities (m/day)
Kawayan	0.30 - 15
Busay 4	0.20 - 11
Hayas 5	0.30 - 15

4.4.4 Conceptual Groundwater Flow Model

The comparison of the discharge time-series to the rainfall time-series at the estimated time lag shows that Busay 4 and Kawayan have similar flow characteristics. Busay 4 and Kawayan (Figure 29 and Figure 30, respectively) show relatively little response to recharge. This is despite a fluctuation in recharge from 500 mm in December 2006 and 350 mm in January 2007 to several consecutive months of near-zero recharge. Busay 4 shows a slight decrease in discharge patterns during the five months of little or no recharge, but Kawayan shows a slight increase during the seven months of no recharge, which corresponds with the increasing rainfall amount during this period. This analysis

supports the previous statistical analysis assertion that both spring aquifers are large relative to the amount of recharge and discharge.

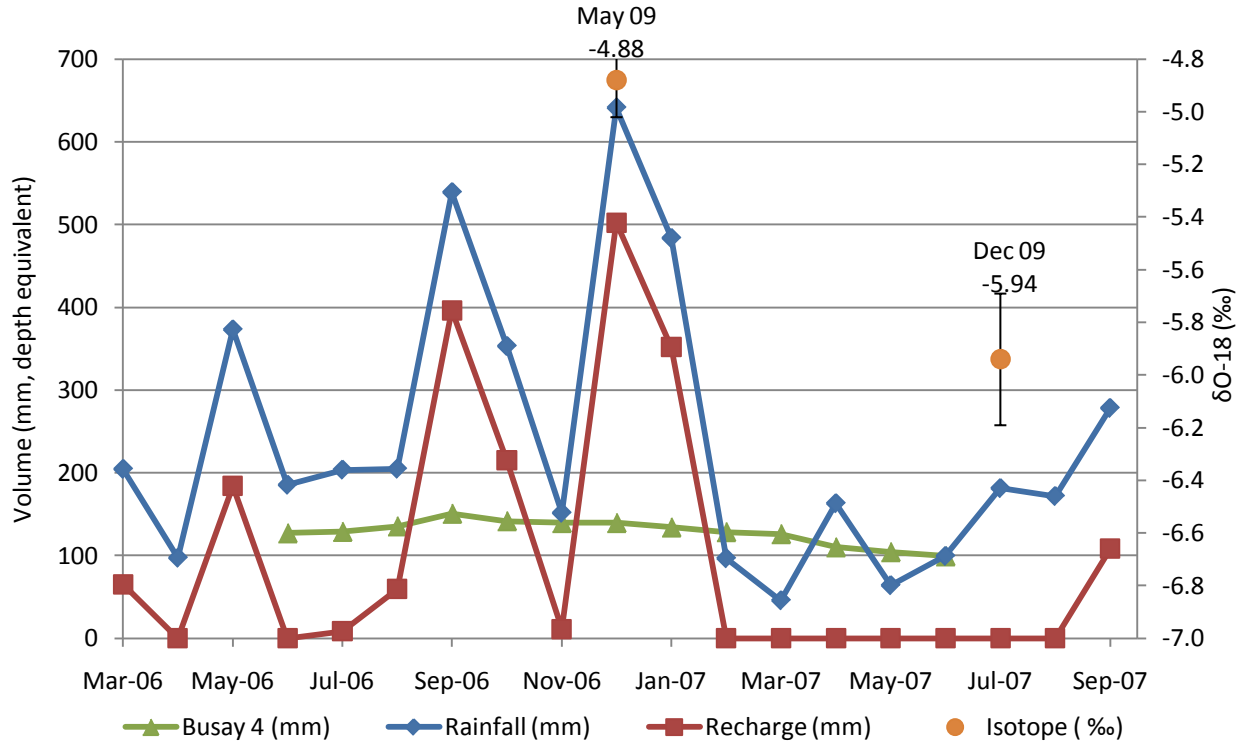


Figure 29. Combined time-series plot of Mar 2006- Sept 2007 rainfall, corresponding TWBM recharge, Nov 2008- Nov 2009 spring unit discharge (A=1 ha), and 2009 $\delta O-18$ values. (Busay 4)

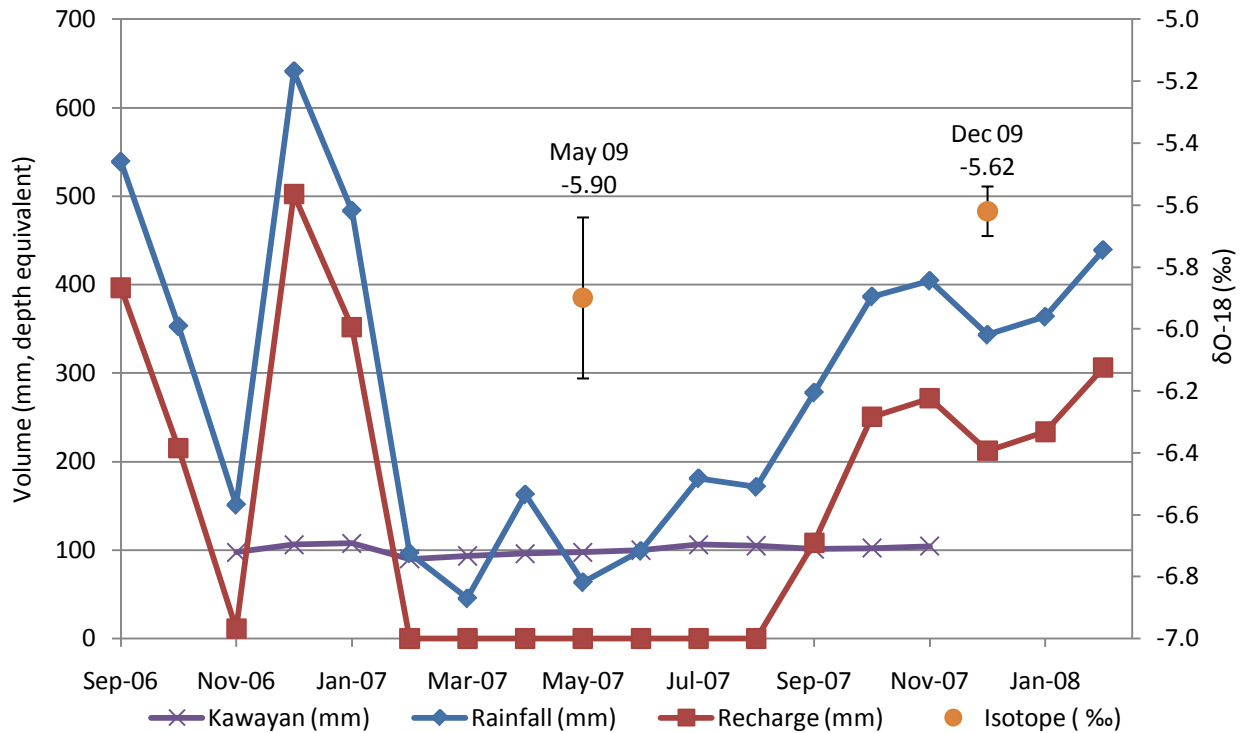


Figure 30. Combined time-series plot of Sept 2006 – Jan 2008 rainfall, corresponding TWBM recharge, Nov 2008–Nov 2009 spring unit discharge (A=31 ha), and 2009 $\delta\text{O}-18$ values. (Kawayan)

For Busay 4, the change in $\delta\text{O}-18$ indicates two flow components. The $\delta\text{O}-18$ (-4.88 ‰) in May 2009 occurs from the injection of a single rainfall/recharge event (a typhoon) mixing with base flow. The base flow component is indicated by the $\delta\text{O}-18$ (-5.94 ‰) in December 2009, during a period of no simulated recharge events for several months. Kawayan shows similar indications of a two-flow components with May 2009 results (-5.90 ‰) representing base flow and December 2009 results (-5.62 ‰) representing a mix of event rainfall and base flow. However, Kawayan requires more data to confirm this observation due to the high uncertainty in the May 2009 results ($\sigma=0.26$ ‰).

Hayas 5 unit discharge shows a response to the rainfall/recharge (Figure 31). The low discharge (52 mm) in July 2007 is attributed to the several months of no prior recharge according to the TWBM. The discharge increases as rainfall increases until peaking to 209 mm in November 2007. This recharge/discharge behavior supports the assertion that Hayas 5 is draining a relatively smaller aquifer. Small discrepancies between the responses of the unit discharge to the recharge exist because the CCA analyzed the rainfall/discharge relationship and not the recharge.

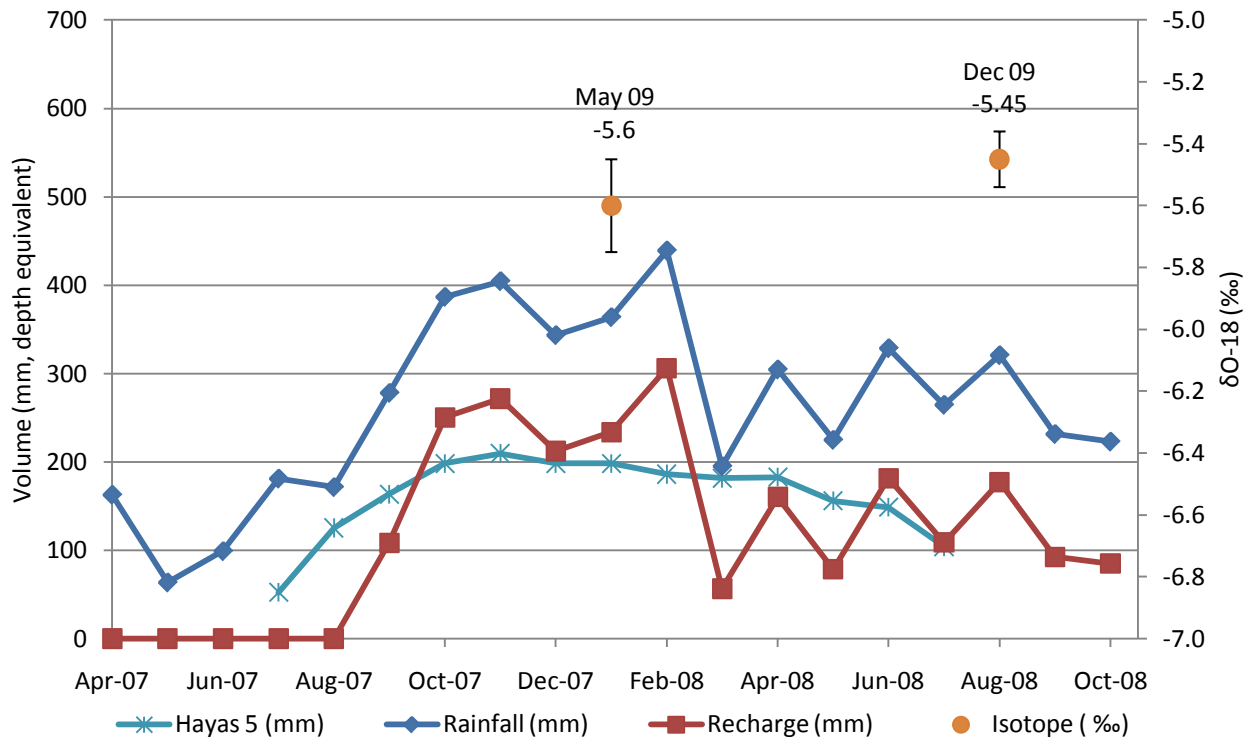


Figure 31. Combined time-series plot of Apr 2007 – Oct 2008 rainfall, corresponding TWBM recharge, Nov 2008- Nov 2009 spring unit discharge (A=16 ha), and 2009 $\delta\text{O-18}$ values. (Hayas 5)

More samples of isotope data are required before conclusions can be drawn about Hayas springs. Both isotope samples were taken during periods of recharge, likely representing a mix of base flow and rainfall recharge. Similar to the Kawayan isotope results, the Hayas isotope results are high in uncertainty.

The synthesis of the information collected from these analyses suggests a relative simple model can accurately represent each spring-aquifer system. This premise is based on the straightforwardness of the methods used to derive reasonable estimates. The estimated recharge area, time lags and aquifer thickness were all within reasonable bounds for the scale of the watersheds. Other estimated values such as hydraulic conductivity fell within the range of published values.

The residence time for Busay 4 is approximately equivalent to the lag time, indicating a slow-mixing flow model in which rainfall events flow through the aquifer system and do not mix completely. Hayas 5 exhibits a similar flow system, since the response of the unit discharge to rainfall events appears within months of the estimated time lag. Kawayan

flow system is uncertain and requires further analysis because the system may be similar to Busay 4 or follows a completely- mixed flow model.

This slow-mixing flow model represents one component of the aquifer system. All springs are perennial even though the TWBM estimates periods of no recharge when ET equals or exceeds P. A second component potentially corresponds to the spring base flow. Kawayan and Busay 4 aquifer transmissivities are probably small since their unit discharges show little response to the period of little or no recharge from February 2007 to August 2007. Hayas 5 probably has a relatively high transmissivity since its unit discharge decreases greatly during the period of little or no recharge and then rebounds quickly with the addition of recharge.

5 Conclusions

5.1 Origin of Spring Water

Analysis of the water origins indicates that all springs are meteoric. All samples, except Busay samples in May, closely follow the LMWL during isotope analysis. The water chemistry analysis supports the isotope analysis results as water temperature, pH level, and low ion concentrations follow closely to expected values for meteoric water. The monthly fluctuation in flow rates also hint at seasonal trends that are associated with seasonal rainfall. The altered isotope composition from Busay Springs results is thought to originate from the addition of typhoon precipitation. Other possible theories for the results, such as evaporation, mixing of alternative water, or error, appear invalid due to the geography of the region, the water chemistry results, and the validity of coinciding sample results.

5.2 Recharge Area

The TWBM estimates at least 45% of the Cagnonoc Watershed area contributes to the estimated average perennial flow rates of Busay Springs and Kawayan Spring and at least 15% of the Ban-Utod Watershed area contributes to the perennial flow rate of Hayas Springs. The TWBM estimates the minimal recharge area since groundwater outflow and interception loss are not included in the model.

The recharge area of Hayas Springs is plausibly within the delineated catchment areas (Figure 19), assuming that the aquifer mimics the watershed's topography. The delineated catchment areas are 80% or larger than the TWBM recharge area estimates. Busay and Kawayan recharge areas extend the entire delineated catchment area (Figure 20) and probably include the adjacent areas of the watershed. The delineated catchment areas are 14-18% less than the TWBM minimal recharge area.

5.3 Aquifer Characteristics

5.3.1 Aquifer Lag Time/Residence Time

Plausible time lags using cross-correlation analysis of rainfall and discharge rates are approximately 16, 24, and 29 months for Hayas 5, Kawayan, and Busay 4, respectively. Estimation of the Busay 4 time lag is supported by the isotope analysis which indicates that precipitation from Typhoon Utor changed the spring flow isotope composition. The plausible time lag of Busay 4 also represents an approximate interflow residence time.

5.3.2 Aquifer Type & Aquifer Connectivity

Kawayan, Busay Springs, and Hayas Springs source from unconnected basalt-type aquifers. Evidence to this argument comes from the isotope compositions and unique flow rate patterns for each of the three spring clusters. Hayas 5 is probably in a different aquifer than the rest of Hayas Springs because the $\delta O-18$ compositions differ by at least 0.35‰ during both sampling periods. The low ion concentration levels found in all springs are common in basalt dominated regions as water undergoes little dissolution before reaching the springs (Ward and Robinson 2000). Also, hydraulic conductivities are estimated within the range for fractured basalts. These multiple aquifers are explainable by the region's volcanic geology with layers of pyroclastic/lava flows of different permeabilities (Fetter 1994, De Vries 1999).

5.3.3 Aquifer Size

Estimates of the aquifers' volumetric size and thickness are summarized in Table 7. The volumetric sizes are likely underestimated for Kawayan and Busay Springs since the discharge rates show minimum fluctuation despite high variability in monthly rainfall. Kawayan 5% CV in discharge and minimum discharge of 10.23 L/s indicates a large aquifer system relative to its annual recharge and discharge. The 28% CV and minimum discharge of 2.80 L/s at Hayas 5 indicates a smaller aquifer system that almost depletes during long periods of no/minimal recharge. As Busay 4 is a connected aquifer to Busay cluster, a 12% CV represents a small fluctuation relative to the total output of the springs.

5.4 Conceptual Groundwater Flow Model of Aquifer

Based on the results from this study, a simple model has been created to describe the spring-aquifer systems. Figure 32 is a visual interpretation.

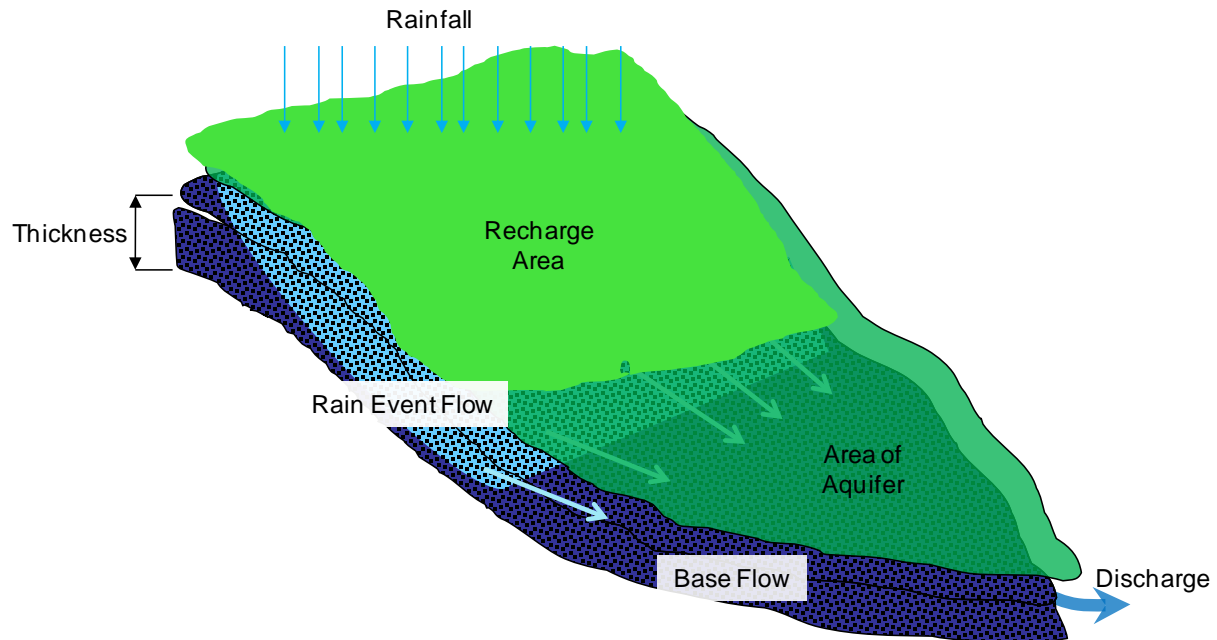


Figure 32. Conceptual model of spring-aquifer system

Recharge probably originates from rainfall within the respective watershed mimicking the watershed topography or from adjacent watersheds through fractured rocks. Kawayan and Busay Springs recharge area is more than 45% of the Cagnonoc Watershed. Hayas Springs recharge area is more than 15% of the Ban-Utod Watershed. This recharge primarily occurs during months of heavy rainfall. Months with little rainfall contribute minimally to the spring-aquifer system due to evapotranspiration and soil-moisture. The rainwater enters the aquifer system as a slug or pulse. This slug travels through the system with some mixing along the basalt aquifer. In Busay Springs, the slug takes less than six months to pass through the spring-aquifer system as indicated by typhoon rainwater passing through the system. Hayas 5 exhibits similar patterns by increasing in unit discharge from 52 mm to 209mm within only four months after several months of no recharge. Kawayan appears similar in flow to Busay Spring but uncertainty lies in the presence of an interflow component. All springs maintain a base flow despite several months of no recharge.

The basic model applies to all three monitored springs and their adjacent springs since the aquifer-types are similar according to analysis. Modifications exist between models of each spring-aquifer system concerning the size of the aquifer.

6 Possible Applications of Conceptual Model in Spring Resource Management

6.1 Spring Production

A mathematical model may be developed in the future to forecast spring production from rainfall patterns. This model would be a tool in drought preparation. Mathematical models depicting groundwater systems with environmental tracers have been extensively studied by Maloszewski et al. (1982, 2000).

For current spring-usage, Hayas 5 is unreliable as a consistent water source. The spring's high transmissivity and small aquifer makes the spring vulnerable during periods of small rainfall amounts. On the other hand, Kawayan is a reliable source for water throughout the year with little fluctuation in discharge. The discharge fluctuations of Busay Springs have a significant impact on water supply since the springs provide approximately 60% of the total water supply. These fluctuations, noted by a 12% coefficient of variation in discharge, must be considered in providing adequate perennial water supply.

6.2 Spring Protection

Spring protection involves the protection of the recharge area. The recharge area was not located with total certainty, but estimates did narrow the range of possible recharge areas. Location of the recharge area for Kawayan and Busay springs are likely the entire watershed above the springs, or the adjacent watersheds. Recharge areas for Hayas springs are probably located in the upper watershed, but are small in size at only approximately 15% of the total watershed. A water budget assessment of the watersheds would improve the certainty of the recharge area locations being inside the respective watersheds.

Since rainfall events pass through the basalt aquifer quickly (<2 yrs) with little mixing or dissolution, the introduction of pollution into the spring-aquifer system will affect the spring discharge quickly.

7 Suggested Improvements to Project Methodology

Additional data would have provided a more detailed model. Data needed for a water balance assessment of the watershed was the stream flow measurements. These measurements were difficult to accomplish due to the rivers shape and the effort required for routine monitoring. However, these measurements would have provided valuable information to calibrate the water balance model and, as stated earlier, improve certainty of the recharge being located within the respective watersheds.

Isotope samples at various times throughout the year would have provided more details about the seasonality of the spring flow and its mixings behaviors. This would have

possibly supported time lag estimates and improved characterization of the groundwater flow model. However, cost-benefit analysis limited the frequency of sampling.

River isotope samples taken at the same time as spring isotope samples would have offered insight into the relationship between stream flow and spring flow. This was not conducted because of cost considerations.

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Appendix A: Visual Classification of the Springs

The basic conceptual model of the hydrogeology began by visually classifying the springs to possible spring-types according to topographical/geological conditions. This classification was used for initially comparing the spring properties to the spring-type's characteristics thereby being able to determine whether the groundwater follows a simple flow system or a more complex flow system.

Spring classification followed part of the system proposed by Bryan (1919) with updated spring definitions by Fetter (1994). Bryan's classification system focused on categorizing the spring water source and the topographical/geological conditions that caused the spring formation. Although definitions appear outmoded, the system is commonly referred to by current authors (Manga 1999, Fetter 1994).

Classification by Bryan first involved identifying the primary water source: defined today as precipitation or non-cyclical groundwater (Dingman 2002). Often, it is easy to differentiate the water source by the properties of the spring. Table 9 shows the typical characteristics of flow rate patterns, temperature, and salinity associated with the water's source. Also listed is magmatic water which doesn't indicate a source of the water but the path of the water.

Table 9. Common Characteristics of Precipitation, Non-cyclical Groundwater and Magmatic Water

	Precipitation	Non-cyclical groundwater	Magmatic water
Flow rate pattern	Seasonal Variation	Uniform flow	
Temperature	Ambient temperature or colder	Several degrees warmer than ambient temperature to boiling	Several degrees warmer than ambient temperature to boiling
Salinity	Varies - often low conductivity	High Conductivity	Varies but high

Next, springs are grouped by the geological formation. The geological formation involves the layers of rock as permeable, semi-permeable, and non-permeable. Variations in spring formation occur based on the rock type. Table 10 summarizes the main geological formation for precipitation sourced waters and variations of each spring type.

Table 10. Basic Classifications of Springs (adapted from Bryan 1919 and Fetter 1994)

Basic Geological Formation	Variations in Spring Formation		Spring-type		
Permeable top layer with abrupt change in topography	Depression on hillsides		Depression Spring		
	Abrupt change in slope at edge of flood plain				
	Depression in flood plains or alluvial plains caused by channel cutting of stream				
	Change in slope at border between alluvial plain and playas, lake beds, or river bottoms; relative imperviousness of central clay deposit assists flow.				
Permeable layer overlies layer with lower permeability	Bottom layer mostly a horizontal and flat surface	Bottom layer extends beyond the permeable top layer; common in sedimentary rock	Relatively soft permeable top layer	Contact Spring	
		Relatively Hard top layer forms a cliff			
	Bottom layer does not extent beyond the permeable top layer; Common in unconsolidated alluvial fans				
	Bottom layer at an incline and flat surface; often, spring on the lowest part of incline	Bottom layer extends beyond the permeable top layer; common in sedimentary rock	Relatively soft permeable top layer		Relatively Hard top layer forms a cliff
		Same as Hardpan	Bottom layer tilts away from hill		Bottom layer tilts into hill, possible in Ravine only
	Bottom layer has irregular surface	Top layer is thick and extents in all directions. Contact occurs at unconformity. Spring at lowest part.			
		Top layer is unconsolidated materials such sediment, volcanic ash, etc. in a basin.			
		Boundary between unconfined and confined water table. Often artesian springs in area			
		Rock protrudes to the surface raising the water table. Often in alluvial fans			
		Fault shifts landscape vertically causing shift in water table			
Confined permeable layer	Confined permeable rock tilted but exposed at upper and lower end. Unusually sedimentary, also alternations of lava flow, flow breccias, gravels		Artesian Spring		
	Confined permeable, folded layers tilted but exposed at upper and lower end.				
	Confined unconsolidated deposit tilted but exposed at upper and lower end.				
	Confined layer conditions similar to other artesian springs but with fractures in top impervious layer				
Impervious Rock	Due to more or less rounded channels in impervious Rocks	Channels in limestone, calcareous sandstones, gypsum, salt		Sinkhole Spring	
		Channels caused by lava flow			
		Channels made by movement of water, tree roots, sand streaks, or shrinkage cracks.			
	Fractures from joints, faults fissures etc. in sedimentary, igneous, or metamorphic rock	Rectangular system of fractures, parallel to the horizon. Common in sedimentary rock and impervious igneous rock (sheeted plutonic rock)		Joint Spring or Fracture Spring	
		Rectangular system of fractures, inclined toward the horizon			
		Inclined fractures, not necessarily systematic			

Appendix B: Temperature & Chemical Data

Temperature data monitored during study (Table 11)

Table 11 Temperature (°C) Measurements of Spring Water

	Busay2	Busay4	Busay5	Kawayan	Cagnonoc River	Hayas 4	Hayas 5	Ban-utod River
May-2009	24.5	24	25	25.5	26.5	26	26	27
Aug-2009	24.5	24.5	25	25	27	26.5	27	26
Dec-2009	25	25	25	25	26	26	26	25

Chemical analysis was done by
 Department of Health Center of Health Development – 8
 Eastern Visayas Regional Medical Center
 Magsaysay Blvd., Tacloban City, Leyte, Philippines
 +63 53 321-3136

or

Michigan Department of Community Health Upper Peninsula Laboratory
 USEPA Region V Drinking Water Cert. No. Mi00035
 PO Box 38
 Houghton, MI 49931
 (906) 487-3011

Table 12. Chloride (mg/L) Measurements of Spring Water

	Busay2	Busay4	Busay5	Kawayan	Cagnonoc River	Hayas 4	Hayas 5	Ban- utod River
Dec-2007	12	8	12	14	12	14	16	--
Dec-2008	9	8	8	10	10	10	12	--
May-2009	BDL	BDL	BDL	BDL	--	BDL	BDL	--
Sep-2009	18	20	22	18	18	20	22	20
Dec-2009	4	4	4	2	2	4	6	2
Mar-2010	--	--	--	BDL	--	--	--	BDL

BDL = Below Detection Level of 4 mg/L

Table 13. Basic Water Chemistry Data of Springs

	Alkalinity (as CaCO ₃) (mg/L)	Acidity (mg/L)	Choride (mg/L)	Total Hard ness (mg/ L)	pH	Total Solid (mg/L)	Calcium (mg/L)	Magnesi um (mg/L)
Dec-2007								
Busay 1	50	4	10	60	7.2	114	24	9
Busay 2	50	3	12	58	7.2	104	26	8
Busay 3	50	4	14	54	7.2	106	24	7
Busay 4	52	4	8	48	7.2	118	26	5
Busay 5	64	10	12	64	6.8	142	30	8
Kawayan	50	4	14	56	7.2	122	22	8
Cagnonoc River	50	4	12	60	7.2	64	26	8
Hayas 1	94	6	12	100	7.1	153	72	7
Hayas 2	98	7	14	102	7.1	155	68	8
Hayas 3	90	9	14	100	7.1	142	64	9
Hayas 4	80	12	14	100	6.8	151	52	12
Hayas 5	100	10	16	116	6.8	174	86	7
Dec-2008								
Busay 1	58	5	8	66	7.2	159	20	11
Busay 2	58	5	9	66	7.2	152	20	11
Busay 3	58	5	10	58	7.2	148	18	10
Busay 4	54	7	8	64	7.1	156	22	10
Busay 5	70	7	8	72	6.8	160	28	11
Kawayan	56	6	10	68	7.2	138	22	11
Cagnonoc River	62	5	10	70	7.4	144	26	11
Hayas 1	94	7	10	98	7.1	174	56	10
Hayas 2	96	6	8	94	7.2	178	60	8
Hayas 3	94	6	10	94	7.2	166	56	9
Hayas 4	80	7	10	86	7.0	159	50	9
Hayas 5	78	7	12	81	6.8	178	48	8
Sep-2009								
Busay 2	56	8	18	48	7.3	148	24	6
Busay 4	56	12	20	44	7.1	142	20	6
Busay 5	70	14	22	56	7.0	180	26	7
Kawayan	60	12	18	66	7.2	152	20	11
Cagnonoc River	68	10	18	60	7.4	156	28	8
Hayas 4	80	18	20	64	6.8	166	38	6

	Alkalinity (as CaCO ₃) (mg/L)	Acidity (mg/L)	Chloride (mg/L)	Total Hard ness (mg/ L)	pH	Total Solid (mg/L)	Calcium (mg/L)	Magnesium (mg/L)
Hayas 5	76	16	22	70	6.8	160	40	7
Ban-utod River	66	10	20	48	7.3	154	26	5
Dec-2009								
Busay 1	38	14	4	38	7.2	132	23	4
Busay 2	42	14	4	38	7.2	94	23	4
Busay 3	42	10	4	36	7.2	100	20	4
Busay 4	42	12	4	38	7.3	116	23	4
Busay 5	56	16	4	50	7.0	90	29	5
Kawayan	48	8	2	38	7.2	88	21	4
Cagnonoc River	52	16	2	40	7.3	146	26	3
Hayas 1	74	14	2	68	7.2	146	56	3
Hayas 2	72	18	2	74	7.2	154	56	4
Hayas 3	72	10	4	64	7.2	152	52	3
Hayas 4	66	22	4	66	7.0	144	50	4
Hayas 5	66	14	6	64	7.0	132	48	4
Ban-utod River	42	10	2	36	7.2	160	28	2

Appendix C: River Isotope Analysis

As shown in Figure 30 the Cagnonoc and Ban-Utod river samples follow close to the LMWL indicating meteoric origins. Each River samples follow identical trends of the upriver sample being more deplete in O-18 and D than near the rivers mouth.

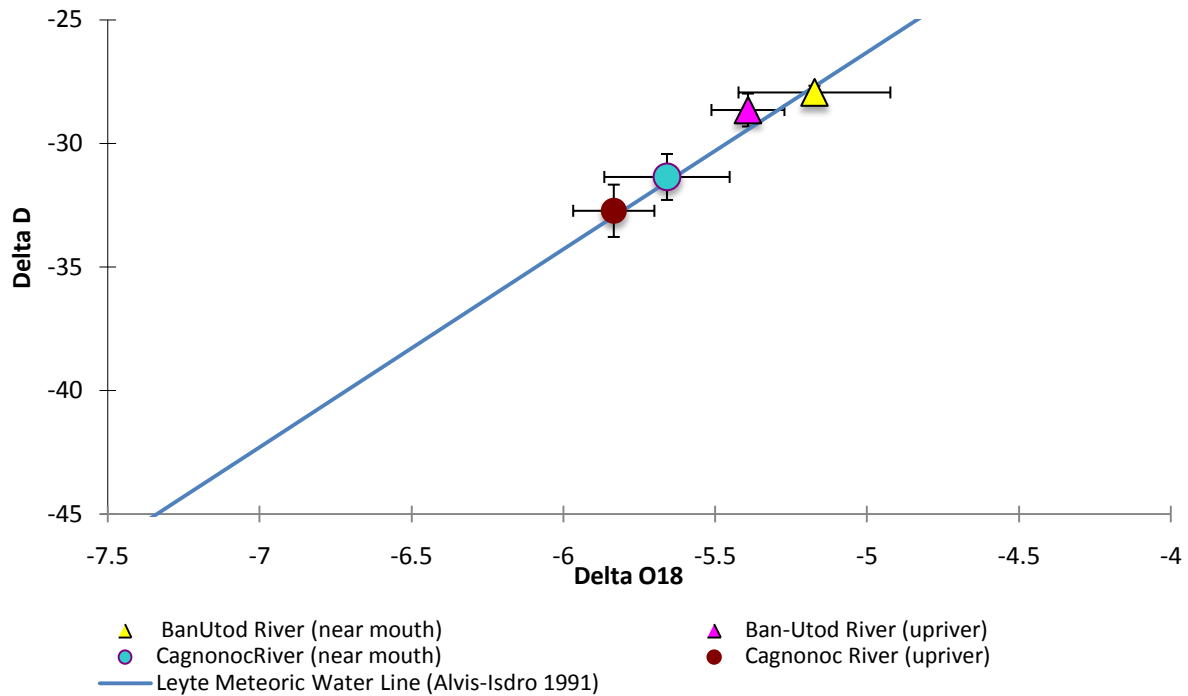


Figure 33. River's March 2010 isotope composition. Vertical and horizontal bars represent standard deviations of δD and $\delta O-18$ values from laboratory analysis, respectively.

Appendix D: Delineation of Watersheds Upslope of Springs

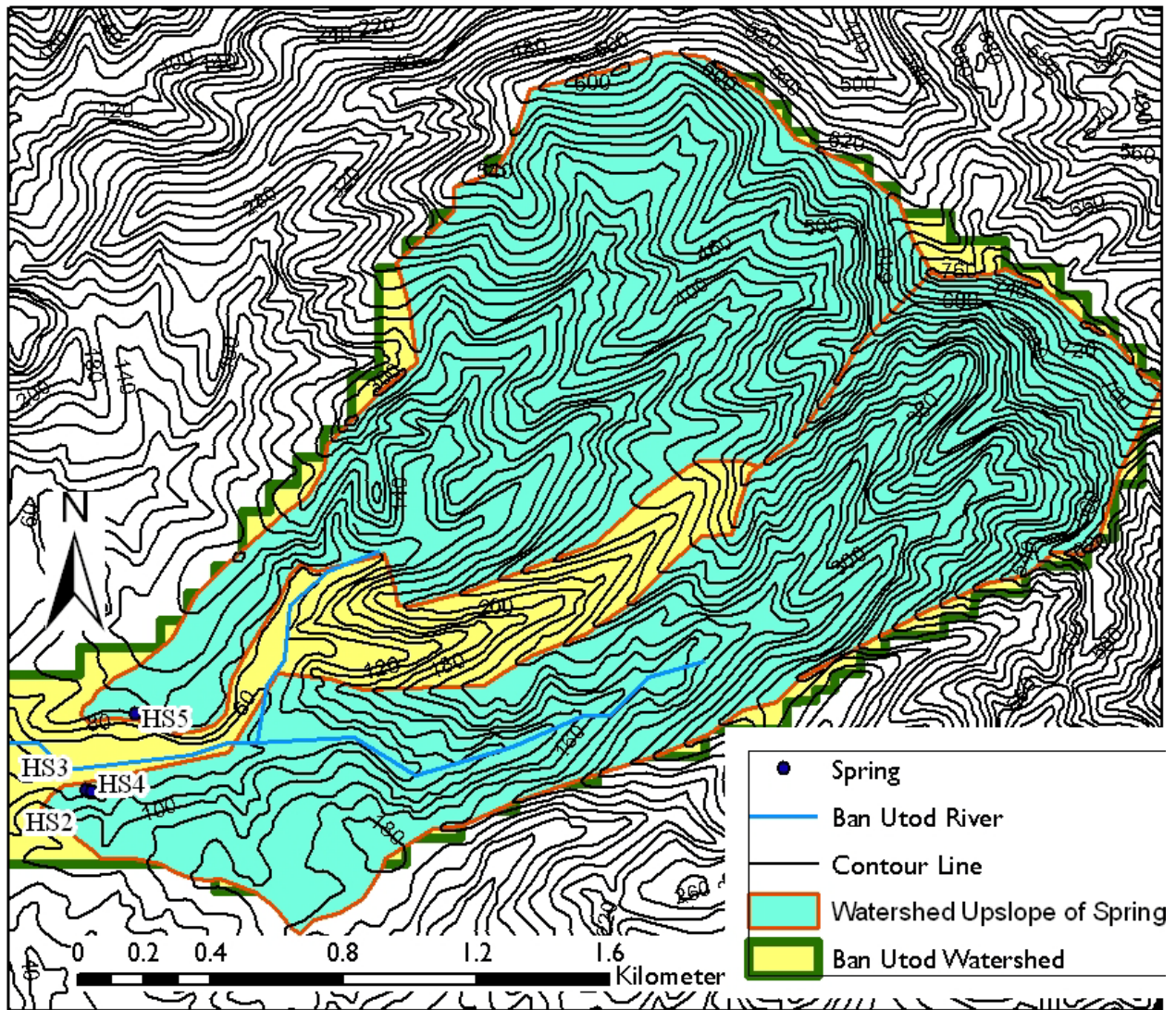


Figure 34. Delineation of catchment areas extending the watershed upslope of Hayas Springs 1-5 (HS#) (image exported from ArcGIS 9).

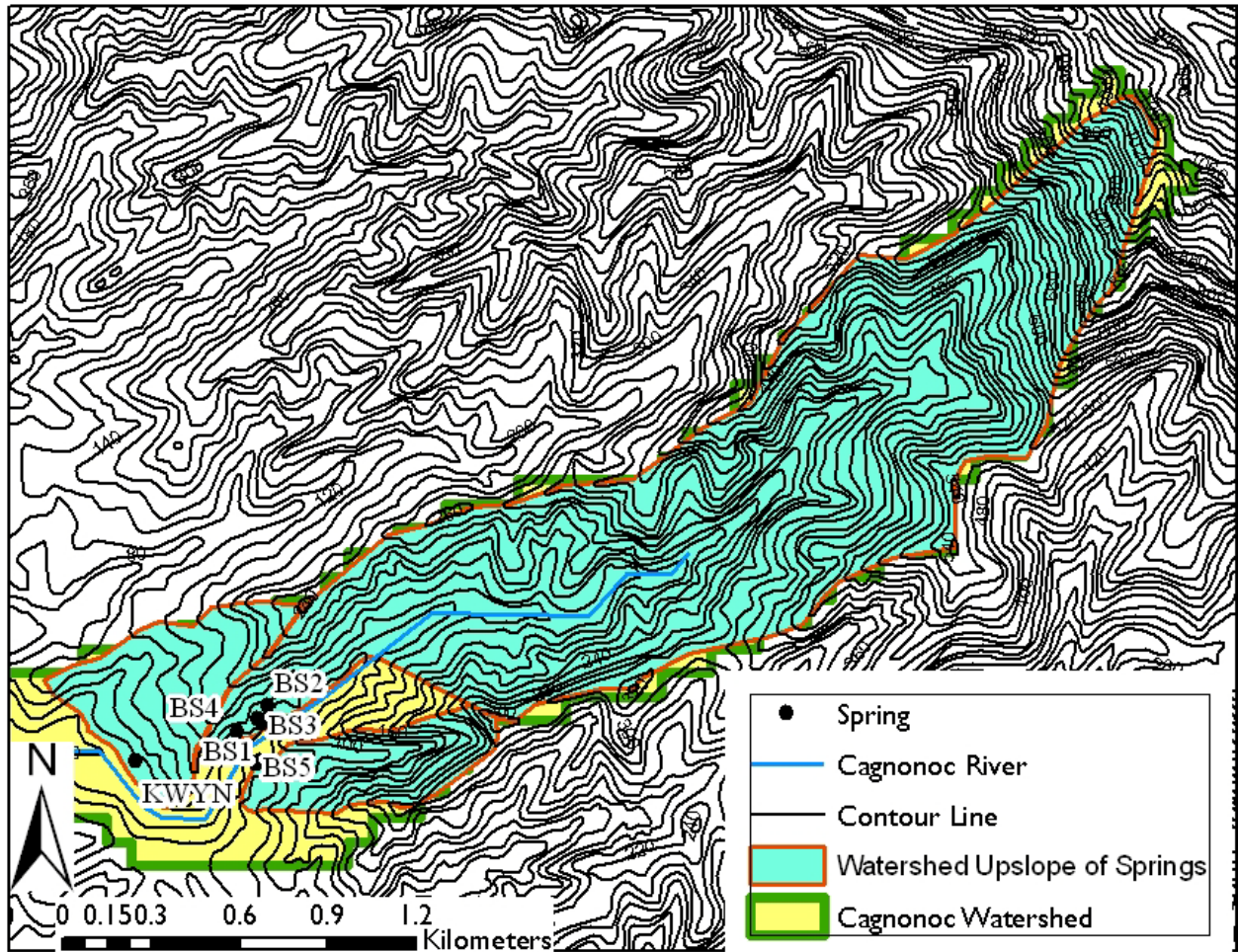


Figure 35. Delineation of catchment areas extending the watershed upslope of Busay Springs 1-5 (BS#) and Kawayan Spring (KWYN) (image exported from ArcGIS 9)

Appendix E: Plot of Daily Rainfall and Spring Discharge (Nov 2008- Nov 2009)

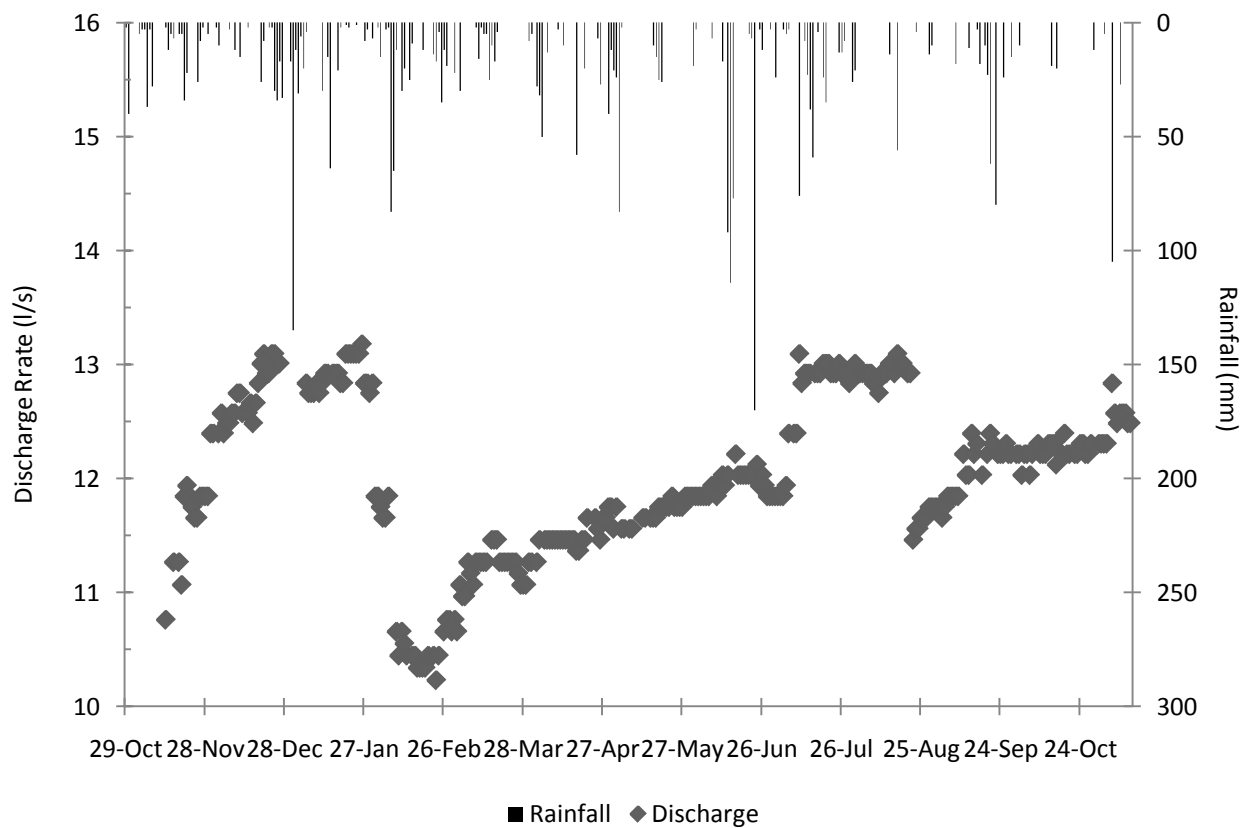


Figure 36. Time series of daily rainfall and discharge rate (Kawayan).

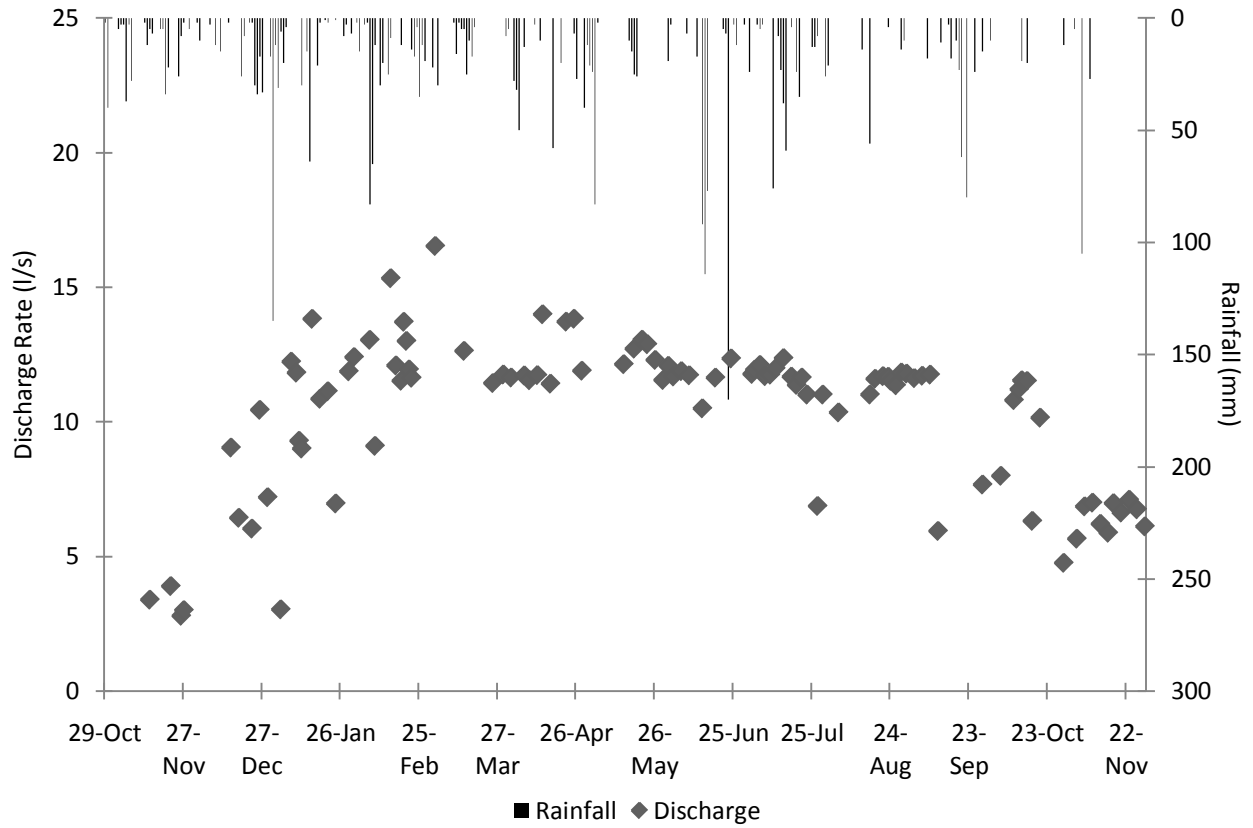


Figure 37. Time series of daily rainfall and discharge (Hayas 5).

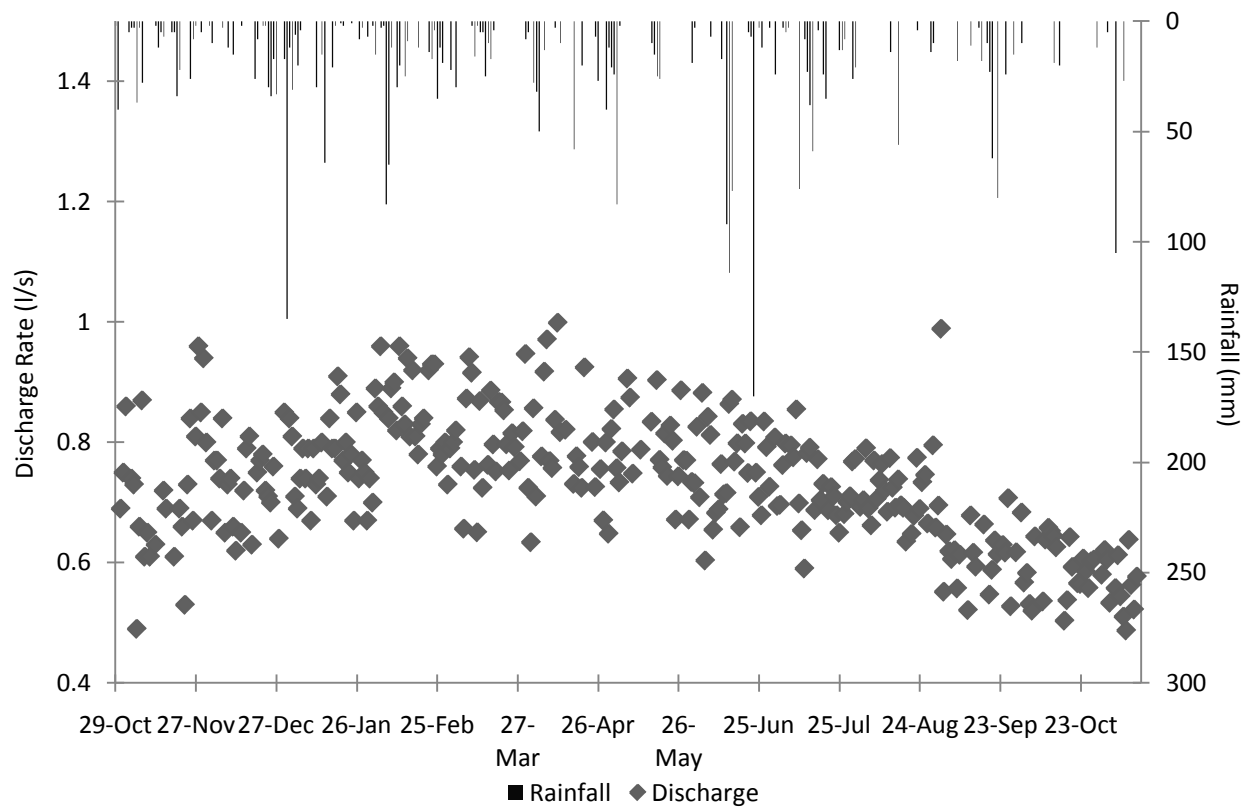


Figure 38. Time series of daily rainfall and discharge rate (Busay 4).

Appendix G: Cross-correlation of Average Monthly Rainfall (1988-2009) to Monthly Rainfall from 2004 to 2009.

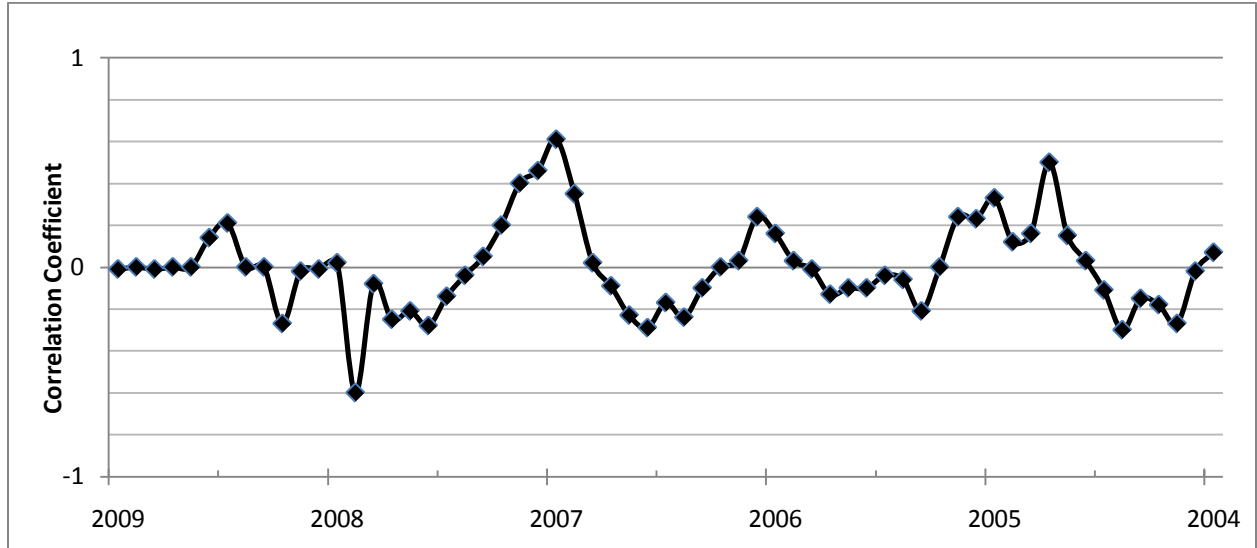


Figure 39. Cross-correlation function of average monthly rainfall (1988-2009) to monthly rainfall from 2004 to 2009.

Appendix H: Scatter Plots of Most Plausible Time Lags

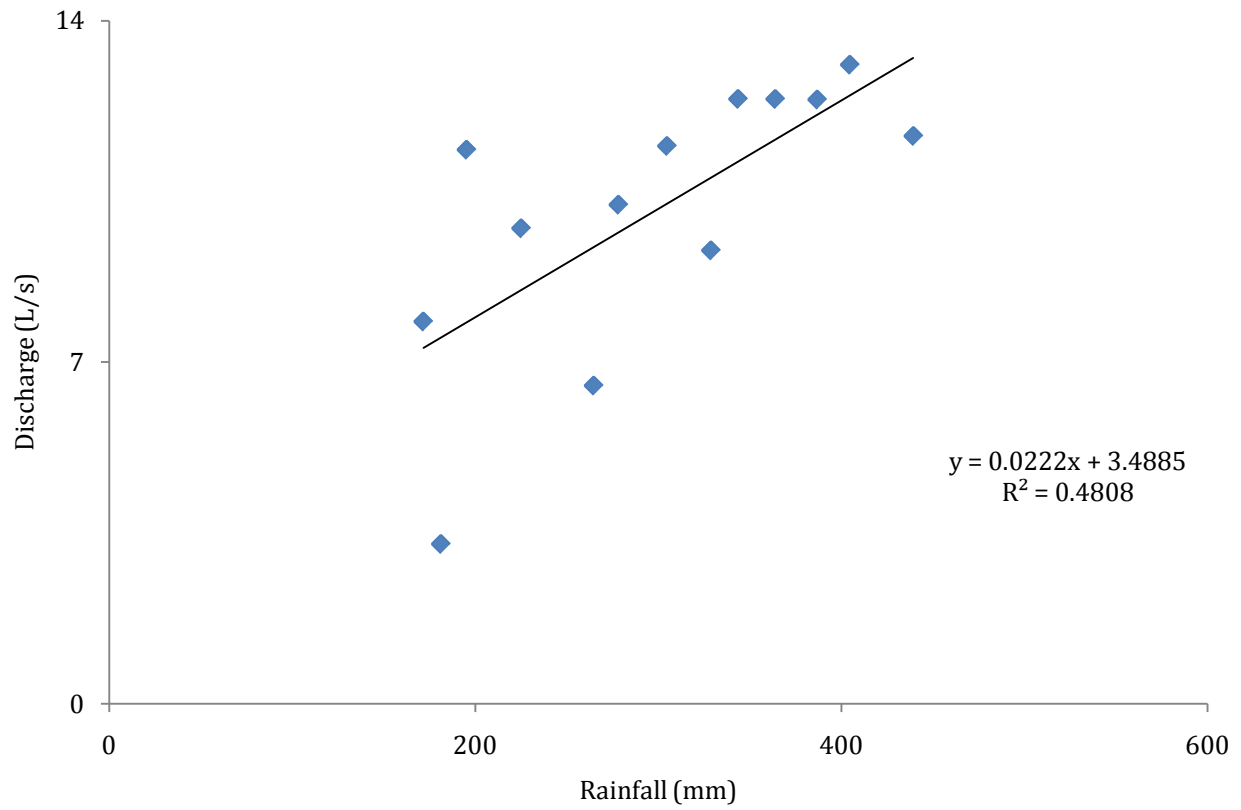


Figure 40. Scatter plot of Nov 2008- Nov 2009 average monthly discharge for Hayas 5 and monthly rainfall of plausible time lag ($T_L = 16$ months) (p value < 0.01).

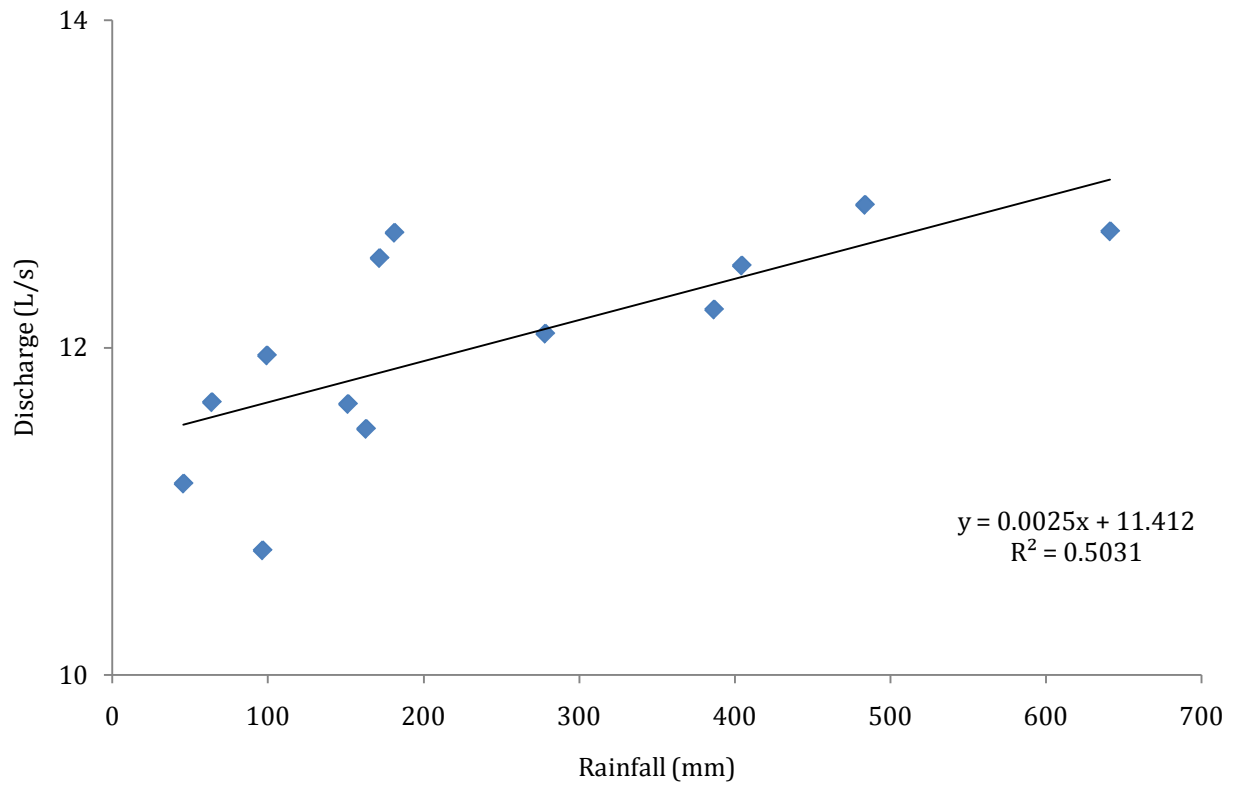


Figure 41. Scatter plot of Nov 2008- Nov 2009 average monthly discharge for Kawayan and monthly rainfall of plausible time lag ($T_L = 24$ months) (p value < 0.01).

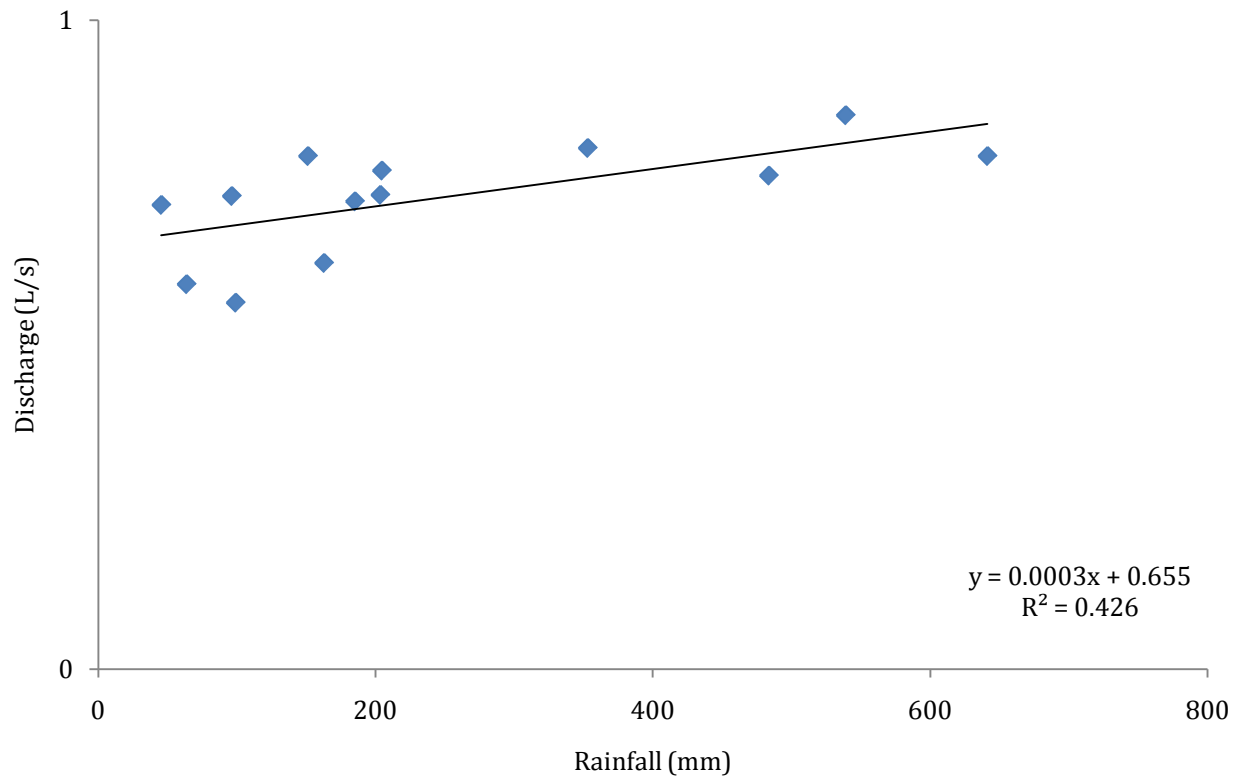


Figure 42. Scatter plot of Nov 2008- Nov 2009 average monthly discharge for Busay 4 and monthly rainfall of plausible time lag ($T_L = 29$ months) (p value < 0.01).