Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Water Resources 28 (2005) 1083–1090
Advances in Water Resources
www.elsevier.com/locate/advwatres

Evaluation of spring flow in the uplands of Matalom, Leyte, Philippines

Cynthia F. Malvicini, Tammo S. Steenhuis *, M. Todd Walter, J.-Yves Parlange, Michael F. Walter

Department of Biological and Environmental Engineering, Cornell University, 216 Riley-Robb Hall, Ithaca, NY 14853-5701, United States

Received 18 November 2004; accepted 21 December 2004
Available online 11 March 2005

Abstract

In order to assess the reliability of the springs near Matalom, Leyte, Philippines as a sustainable source of drinking water, we measured precipitation and outflow of five small and two large springs for the region for a period of a year and analyzed the recession spring flow data. Although monthly spring flow follows a similar pattern to that of the rainfall, the regression relationship between both parameters is poor except for the smallest spring. To determine the dry season spring flow behavior, we analyzed the spring flow data with a mechanistic recession flow model originally developed for prediction of stream drought flow in the northeastern U.S. by Brutsaert and Nieber in 1977. The model describes the dry season spring flow well assuming that the aquifer behaves as a linear reservoir. The analysis shows that the flow "half-life" for the springs is about one month. By adding the individual spring flows to derive a watershed outflow we were able to evaluate how well the simple watershed geometry underlying the analysis of Brutsaert and Nieber [Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 1977;13(3): 637–43] applies to the more complex watersheds.

1. Introduction

Establishing environmental priorities is often difficult in developing countries where the need to improve health and economic conditions is vitally important. In many developing countries, a reliable, clean water supply for drinking and domestic use is a basic need. In the uplands of Matalom, Leyte, Philippines, where this study was carried out, year-round access to drinking water is a serious concern (Fig. 1).

The calcareous uplands of Leyte are commonly deforested and experience periodic droughts or diminished flow. Drought is particularly problematic for upland residents who rely on natural springs for their domestic water supply. Malvicini [11] found that residents in the Leyte uplands who rely on spring flows do not have a sufficient amount of water for one to twelve months of the year for sustaining proper health [9].

The objective of this study was to assess the reliability of the springs as a sustainable source of drinking water by analyzing the flow characteristics. We characterized the dry season spring flows by applying a procedure developed by Brutsaert and Nieber [6] and Brutsaert and Lopez [4] to a calendar year worth of spring flow data. In addition, we tested the limitations of the simple geometry for total watershed outflow of the unrealistically simple geometry employed in this analysis. This study can be employed by other areas to help design reliable spring flow water supply systems.

2. Study area and relevant data

Eight natural springs were chosen for this study, two of which are considered large for the area. The springs

* Corresponding author. Tel.: +1 607 255 2489; fax: +1 607 255 4080.
E-mail address: tss1@cornell.edu (T.S. Steenhuis).

0309-1708/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.advwatres.2004.12.006

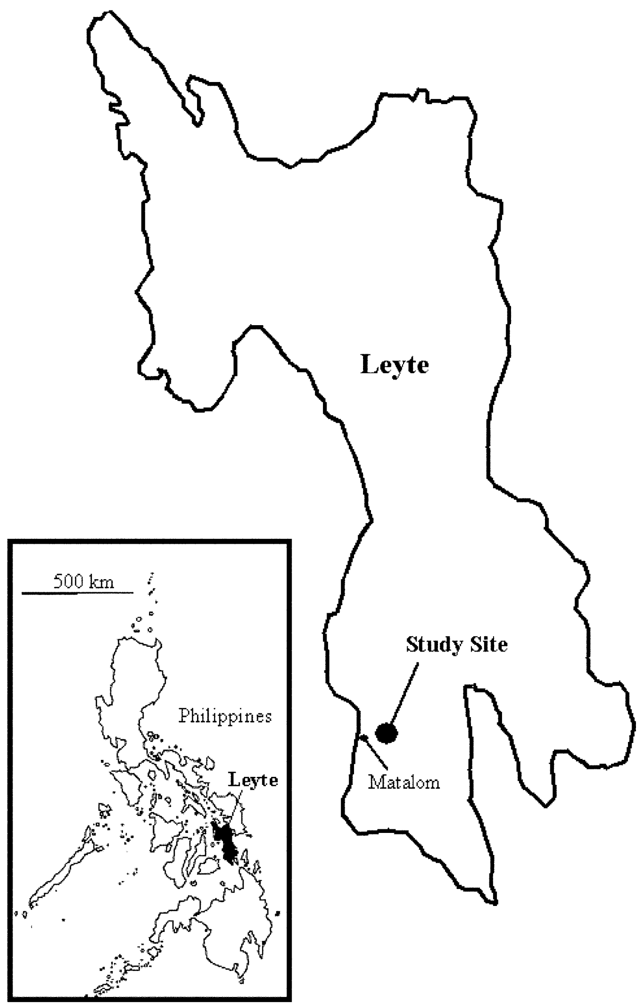

Fig. 1. Location of experimental site near Matalom, Leyte, Philippines.

are located in the barangay (or village) of President Garcia approximately eight kilometers southeast of the municipal center of Matalom (10.3°N, 124.8°E), Leyte, Philippines. The sites are situated at 40–100 m above sea level at hillsides of 20–42% slope [11]. Although we attempted to choose springs that represent a diversity of land uses, all springs in the barangay are situated on land either owned or leased to farmers, and we could not control how the plots surrounding the springs were managed. The study area was within a 1 km radius. The contributing watershed was larger than the 1 km radius, but could not be determined because it did not coincide with the topographic boundaries.

The geomorphology is of dissected calcareous shale or karst limestone, with shallow soils, moderately stony and severely eroded. According to a macroscale soil survey of the uplands of Matalom, the predominant soil type is the Eutropept of the Lugo series [8].

Springs are scattered throughout the hillsides, most of which are the products of perched water tables within the limestone. Springs are the primary source of all domestic water. In order to sustain spring flow through the dry season, rain must infiltrate and percolate into the karst. The most effective percolation pathways are macropores, however, surface disturbance through tillage or compaction can plug these pathways, diverting the water to runoff or return flow. Chandler and Walter [7] identify the primary hydrologic flow pathways in the Matalom uplands as surface runoff and shallow interflow for most land uses. Further descriptions of the study area may be found in [7,10,11,17].

3. Theory

Outflow of springs one or more days after precipitation in a karst region can be assumed to occur from upstream aquifers along the underground flow path to the spring. This type of flow is known variously as base flow, drought flow, or low flow [4]. For the analysis of the spring outflow, we used the procedure developed by Brutsaert and Nieber [6] for stream flow recession analysis. Declining groundwater reservoirs control both stream baseflow recession and upland spring outflow recession and, thus, the method should be equally valid for both situations. One advantage of this method is that it is independent of the ambiguity inherent in identifying when drought flow starts. Recent refinements on the method have been made [4,5,13,18,19].

This drought flow analysis is based on the Boussinesq equation [1,2], which describes flow in unconfined aquifers. There are three theoretical solutions of the Boussinesq equation that have the general form of a power function [6]:

$$\frac{dQ}{dt} = -aQ^b \tag{1}$$

where Q is the recession flow $[L^3T^1]$, t is time, and a and b are constants. The coefficient a can be directly related to the groundwater reservoir's characteristics and b is an exponent whose value depends on the time scale. Parlange et al. [14] support earlier results [3,4,16] showing that each of the three solutions is applicable to one of two distinct, temporal recession flow regimes. One regime is associated with short-time flow and another with long-time flow.

Short-time flows generally have a higher Q than long-time flows. Brutsaert and Lopez [4] showed the following solution for short-time flow:

$$a = \frac{1.13}{kfD^3L^2}, \quad b = 3 \tag{2}$$

where K is the hydraulic conductivity $[LT^{-1}]$, f is the drainable porosity, D is the aquifer thickness $[L]$, and L is the total length of upstream channel intercepting groundwater flow $[L]$.

The long-time flow behavior is of greatest interest in this study because it can be used to predict the quantity and duration of Leyte's spring flow. One long-time solution is [4,6]:

$$a = \frac{4.80K^{0.5}DL^2}{fA^{1.5}}, \quad b = 1.5 \tag{3}$$

where A is the upland drainage area. Henceforth, Eq. (3) will be referred to as the Brutsaert solution as he appears with co-authors on several papers that develop and utilize this solution. Another long-time solution that is frequently used is the linear reservoir solution [3]:

$$a = \frac{0.35\pi^2 KDL^2}{fA^2}, \quad b = 1 \tag{4}$$

One advantage of the linear reservoir solution is that a flow "half-life", "$t_{1/2}$", can be determined independently from the flow at any given time:

$$t_{1/2} = \frac{0.69}{a} \tag{5}$$

To date, this drought flow analysis has been applied to streams [4,6] but not to springs. Spring hydrographs might actually be more appropriate because they only drain the groundwater and are not sensitive to bank storage or precipitation-related components. They might be, therefore, a better indicator of hydraulic characteristics of drought flow of the watershed than stream flow hydrographs.

4. Methods

Daily precipitation measurements were taken with one tipping rain gauge, centrally located in the study area, for one year beginning July 1995. Additional measurements were taken daily April–June 1997.

The discharge of the six smaller springs was measured with a container of known volume and a stopwatch collected off a piece of bamboo in the spring orifice that was inserted by the residents. Discharge of the two larger springs was calculated using the midsection computed method as the product of the velocity and the cross-sectional area. The velocity was measured with a Gurley Pygmy Current Meter. All spring flow data are for one calendar year, gathered from July 1995 to March 1996 and April to June 1997. Measurements were taken almost every day, at the same time each day, and always following a storm event.

Discharge characteristics were investigated using the theory above with particular emphasis on the long-time, or drought flow, recession behavior using the linear reservoir, $b = 1$, and Brutsaert, $b = 1.5$, solutions to Eq. (1). Eq. (1) was fit to the data in the form of $\ln(dQ/dt)$ vs. $\ln(Q)$. Before applying this drought flow analysis, we identified episodes in the record that represent strictly drought flow conditions. Brutsaert and Lopez [4] found that the choice of data is critical; the time period between each rain event and the data selected should be as short as possible. For the small springs, we included discharge measurements that were in recession for at least four consecutive days following a rain-event day. We excluded data for which more than 20 mm of rain fell within the recession period. To eliminate residual storm flow, we further restricted the criteria for the large springs to include recession periods with no rain of more than 10 mm and no significant storm events occurring in the previous three days.

With actual recession flow measurements Q_i and Q_{i+1} at successive times Δt apart, Eq. (1) can be expressed as:

$$\frac{Q_i - Q_{i+1}}{\Delta t} = a\left(\frac{Q_i + Q_{i+1}}{2}\right)^b \tag{6}$$

Brutsaert and Lopez [4] reasoned that the smallest dQ/dt for a given Q represents the drought flow. This is because the decline in groundwater outflow into natural rivers is markedly slower than that of other stream flow components related directly to precipitation events or channel storage. Thus, in a graphical representation of $\ln(dQ/dt)$ vs. $\ln(Q)$, the constants a and b can be found from the intercept and slope, respectively, of the lower envelope of the data. There is some ambiguity to draw the lower envelope. We choose the line in such a way that it contains 90% of the data points above the line.

5. Results and discussion

5.1. Precipitation

President Garcia received 1764 mm of rainfall during the period of study (July 1995–March 1996 and April 1997–June 1997), with 184 days of rainfall and 98 days where the rainfall exceeded 5 mm [11]. A distinct seasonal precipitation pattern was evident. The wet season was from August to February and was characterized by monthly rainfalls of 200–400 mm, with the exception of November, which was relatively dry (113 mm). The dry season was from March to May, with an average of 68 mm of rain per month.

There is no apparent long-term trend in total annual precipitation in the southwestern region of Leyte. Rainfall is variable even within a 5 km radius in the Matalom upland, suggesting strong local effects on weather. Historic precipitation data from another barangay approximately 4 km from the study site indicate an erratic pattern in total precipitation from year to year. The wettest year in a 10-year record was 2670 mm and the driest year was 1190 mm. However, the seasonal trend remains constant, namely the pronounced dry season begins in

February or March, reaches it peak in May, and ends by July [7].

Data recorded at the time of this study by the Visayas State College of Agriculture in three neighboring barangay indicates the study site as a lower rainfall area. Based on the data we have for the area, we can infer that the study year represents an average to dry year.

5.2. Discharge

Fig. 2 shows that mean monthly spring flow follows a similar pattern to that of the rainfall. In all springs, mean monthly discharge rates lag behind total monthly precipitation. As expected, spring flow response for the larger springs lags further behind rainfall than for the smaller springs; this is most evident comparing the peak monthly spring flows following the January peak in precipitation (Fig. 2). Table 1 shows the monthly and seasonal spring flows for each spring.

To evaluate immediate spring response to rainfall, we analyzed the relationship between spring discharge and precipitation on the same day and found six of the springs positively but weakly correlated ($R^2 = 0.38$–0.49). The smallest spring (Abgaw) was the most strongly correlated ($R^2 = 0.70$) and rainfall and flow were essentially uncorrelated for the largest spring, Sinti ($R^2 = 0.08$).

The Kikoy spring dries each year but then has a higher wet season average flow than all other small springs (Table 1). Residents claim it increases in flow within two hours after a storm event. The contributing area of the Kikoy spring has traditionally been left fallow for as long as the farmer could recall and was covered intermittently by small shrubs at the time of the study. The Kikoy spring did not start flowing until a month after the beginning of the rainy season; that month received 130 mm of rain. This delay suggests the soil in the spring recharge area needs to reach saturation before the spring starts to flow and that groundwater reservoir storage may be small compared to the other springs. Based on Chandler and Walter's [7] observations, the process of saturating the soil is probably slow; their fallow site in nearby Matalom produced surface runoff with as little as 4 mm of rain, i.e., very little water infiltrated.

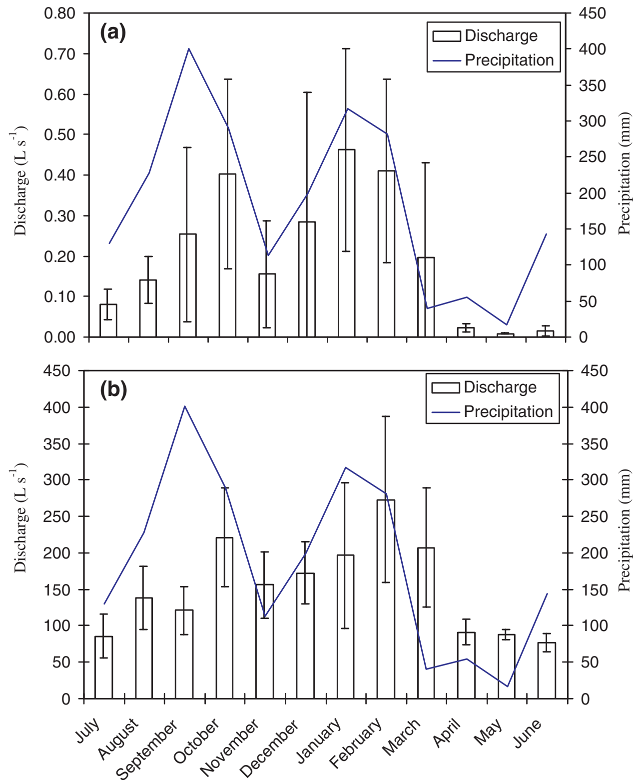

Fig. 2. Comparison of mean monthly discharge and precipitation for (a) small and (b) large springs. Error bars are ± one standard deviation of the flows among springs.

Table 1
Monthly and seasonal spring flows, Q (L s^{-1})

Month	Small springs						Large springs	
	Abgaw	Betoy	Estot	Juliana	Kiroy	Liboy	Sinti	Tinubdan
July	0.0030	0.26	0.01	0.11	Dry	0.10	93	79
August	0.0052	0.39	0.03	0.20	0.08	0.14	132	145
September	0.0098	0.36	0.13	0.25	0.61	0.16	131	111
October	0.0101	0.43	0.27	0.58	0.95	0.18	247	195
November	0.0062	0.22	0.12	0.19	0.31	0.09	183	129
December	0.0100	0.36	0.15	0.42	0.59	0.16	185	160
January	0.0092	0.30	0.31	0.53	1.44	0.18	190	203
February	0.0089	0.33	0.29	0.57	0.99	0.28	289	257
March	0.0050	0.21	0.18	0.31	0.35	0.13	259	155
April	0.0028	0.03	0.03	0.03	Dry	0.04	107	76
May	0.0017	Dry	0.01	0.02	Dry	0.02	115	61
June	0.0023	Dry	0.01	0.05	Dry	0.02	94	59
Wet Season	0.0084	0.34	0.19	0.40	0.73	0.17	198	177
Dry Season	0.0022	0.01	0.01	0.04	Dry	0.02	105	64

5.3. Drought flow

Two approaches to the drought flow analysis were investigated. The first looked at the individual springs independently and the second looked at the lumped spring data for the small and large springs, respectively. For each approach, we did two determinations. First, for each individual spring we regressed $\ln(dQ/dt)$ vs. $\ln(Q)$ to find the average slope b_{avg} for each set of spring data. Secondly, we obtained the a in Eq. (1) using the linear reservoir solution, $b = 1$. For the latter, we delineated lower boundaries with a straight line in accordance with the method originally proposed by Brutsaert and Nieber [6]. The position of the lower boundary may be subject to substantial bias due to relatively few errant data on the lower edge of the cluster so a was set such that 90%, or as close as possible when data were limiting, of the data lay above the envelope. Though short-time flow was not central to this study, a similar technique was used in some instances to place the short-time boundary using $b = 3$.

Fig. 3 shows the results for the largest and smallest of the small springs, and Table 1 summarizes the results for all the springs. From the linear regression, the average b_{avg} for all the springs was 1.35, which is between the linear reservoir solution, $b = 1$, and the short-time solution, $b = 3$. Because the average slope is 1.35, the Brutsaert solution, $b = 1.5$, does not apply here. Applying Eq. (5) to the a coefficients determined from the linear reservoir solution, the flow half-life, $t_{1/2}$, was calculated for each spring (Table 2). For the small springs, the average $t_{1/2}$ is 34 days and for the large springs it is 14 days. In other words, with no recharge, the discharge from the small springs will decrease by a factor of two every 34 days and the same will happen to the large springs every 14 days. Though it is not central to this study, the short-time, $b = 3$ line in Fig. 3a and b appears to delineate an upper boundary for each spring. Comparing Fig. 3a and b, note that the placement of the short-time boundary is unique to each spring. This agrees with the previously mentioned lack of unified correlation across springs with respect to immediate spring response to rain.

Because of the limited data for any one spring, the data were also analyzed as two lumped sets, one for the large and one for the small springs, to improve our confidence in our flow half-life estimates. These data and the envelopes are shown in Figs. 4 and 5 for the small and large springs, respectively. The data from different springs form a single cloud of data for the small and large springs. This similarity of recession flow character illustrates that the local landscape and climate are the primary controls on flow behavior. The primary difference among the springs is flow magnitude, which is controlled by the spatial extent of the upland recharge area. The long-time boundaries were delineated using the linear reservoir solution in the same manner as for the individual springs. The $b = 3$ line was not included in the figures because, as mentioned above, this short-time flow envelope is spring-specific.

For the small springs, the linear regression line, $b = 1.35$, shown in Fig. 4, correlates better with lumped data, $R^2 = 0.80$, than any of the individual linear regressions

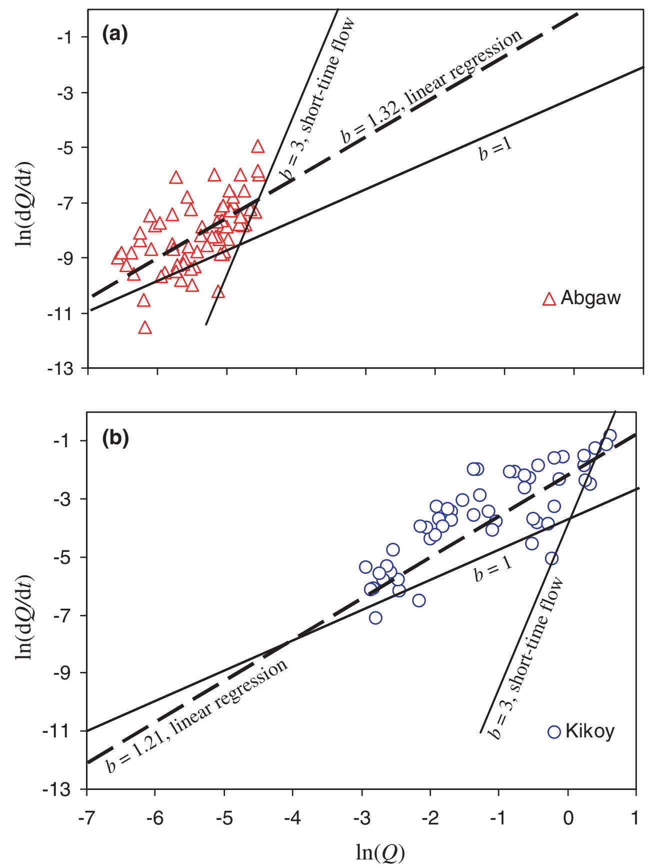

Fig. 3. Drought flow analysis for the (a) Abgaw and (b) Kikoy springs; both are small springs. The symbols indicate data, the dashed lines show the linear regressions, and the solid lines show the short ($b = 3$) and long ($b = 1$) time drought flow envelopes.

Table 2
Drought flow linear regression results

	n^a	Linear regression			Linear reservoir $b = 1$	
		a^b	b	R^2	a^b	$t_{1/2}$
Small springs						
Abgaw	68	0.37	1.32	0.35	0.022	31
Betoy	44	0.07	0.91	0.58	0.027	25
Estot	71	0.20	1.33	0.76	0.025	28
Juliana	61	0.22	1.38	0.62	0.017	42
Kikoy	52	0.12	1.20	0.66	0.025	28
Liboy	78	0.48	1.76	0.75	0.014	51
Large springs						
Sinti	36	0.018	1.28	0.44	0.041	17
Tinubdan	30	0.016	1.37	0.65	0.061	11

[a] Number of recession data points used in the analysis.
[b] The a coefficients are in units of [day^{-1}].

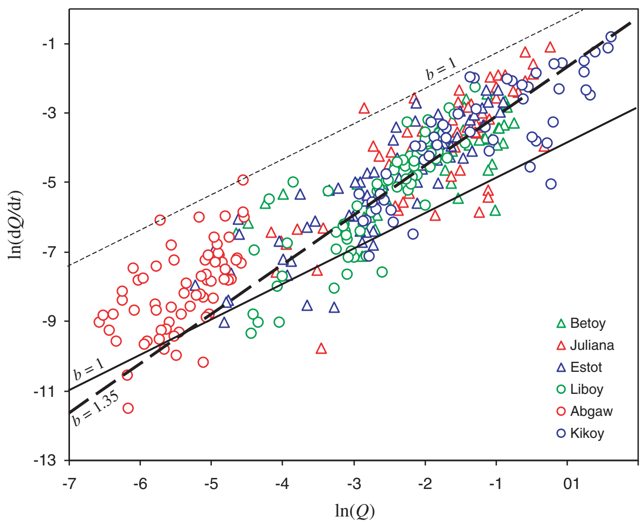

Fig. 4. ln(dQ/dt) vs. ln(Q) for all of the small springs. The lines show different approaches to determining envelopes for recession flow behavior.

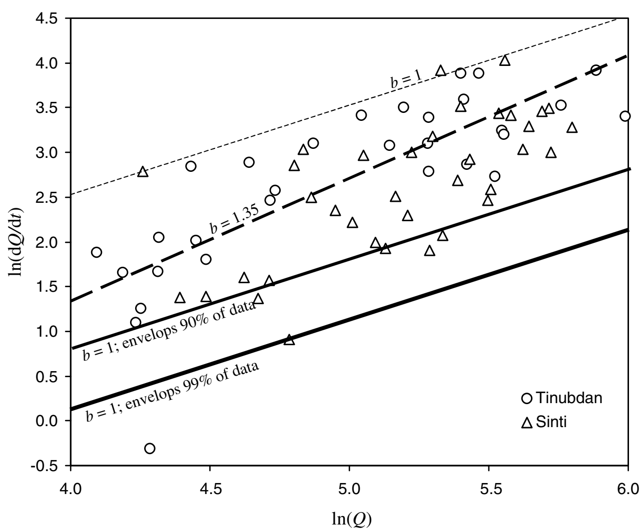

Fig. 5. ln(dQ/dt) vs. ln(Q) for all of the large springs. The lines show different approaches to determining envelopes for recession flow behavior.

correlated with individual spring data (Table 2). The linear reservoir method results in an $a = 0.022\ \text{day}^{-1}$. If we use the linear reservoir fit to characterize the small-spring flow, the discharge half-life is 31 days. This is close to the average flow half-life from the individual spring analyses. Interestingly, employing the same methodology used for the lower boundary, the upper boundary appears to be best fit with $b = 1$. Though this 1:1 upper boundary is evident in data presented in other drought flow studies [4,12] the significance is not clear.

For the large springs, the linear reservoir method results in an $a = 0.041\ \text{day}^{-1}$. Using Eq. (5), the flow half-life for the large springs is 17 days. Using a more stringent approach to place the envelope such that 99% of data lies above the line (Fig. 5) results in a flow half-life of 35 days, which is similar to the small springs. The increased stringency may be justified because there were probably less erroneous data points associated with the large flow magnitudes characteristic of the large springs than there was with the small springs. The sparseness of data prevented a meaningful placement of the short-time envelope in Fig. 5. As in the small springs, an upper envelope is well represented by a line of slope 1 (Fig. 5).

5.4. Implications

This study is also of interest because it gives insight as to why the Boussinesq equation has fit so well to data in other studies using watershed-averaged parameters [4,6,16]. These watersheds were not homogeneous at all and yet the outflow behavior has been described well with one set of parameters. In our study, we have data for several sub-portions of the watershed, but we do not know the overall outflow. We can, however, construct the total flow by adding all the spring flows:

$$Q_\tau = \sum_{i=1}^{n} Q_i \tag{7}$$

Fig. 6 shows a storm hydrograph for the two large springs and a hydrograph constructed using all of the

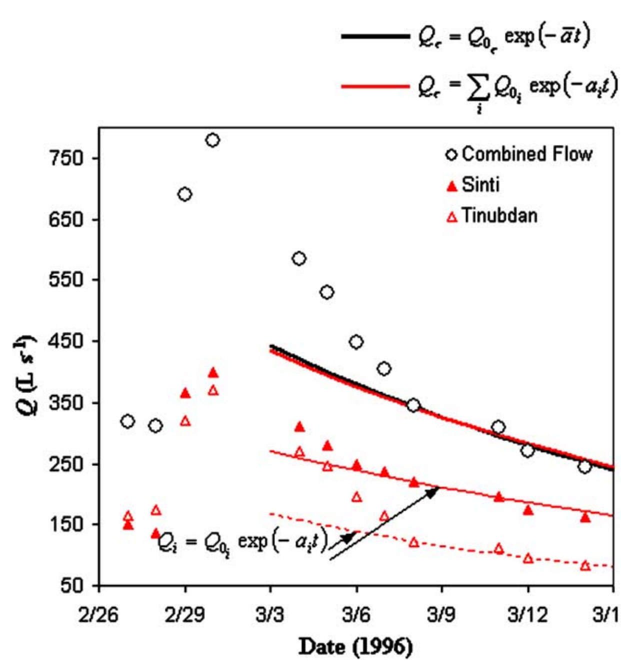

Fig. 6. Hydrographs for the two large springs, Sinti and Tinubdan (red in web version), and the combined flow from all of the springs (black). The exponential recession curves from Eq. (8) are superimposed on the data. The linear reservoir constants, a_i, are taken from Table 2 and $\bar{a}$ is the average of the a_i coefficients from the two large springs.

springs. Because the combined flow of the large springs contributes over 95% of the total flow we have not shown the individual small spring flows in Fig. 6.

Analytically, from the linear reservoir theory, the recession flow for each individual spring can be expressed as an exponential decay, $Q_i = Q_{0_i}\exp(-a_i t)$. If the behavior of all the individual springs is similar, i.e., their individual a_i coefficients are similar, then the total outflow should have a recession constant, a, similar to the individual springs:

$$\sum_{i=1}^{n} Q_{0_i}\exp(-a_i t) = Q_{0_\tau}\exp(-\bar{a}t) \quad (8)$$

Fig. 6 shows a well-behaved composite hydrograph for a period without rain and recession curves based on Eq. (8) for the combined flow from all the springs and for the two large springs individually; the small springs contributed less than 1% to the total and were not included to avoid clutter. In Eq. (8), Q_0 can be specified at any time during the recession flow. Here we choose to define Q_0 as the average flow on March 8 and 11 and $t = 0$ on March 9; this approach avoided over-emphasizing any one point in determining the placement of the curves. The heavy red line (web version) in Fig. 6 corresponds to the left side of Eq. (8) and the heavy black line in Fig. 6 corresponds to the right side of Eq. (8). They are essentially the same corroborating the equality in Eq. (8).

Fig. 6 shows the transition between short- and long-time flow for the two large springs (triangles in Fig. 6), i.e., the point when the recession data first begins following the linear reservoir model, $Q = Q_0\exp(-at)$. Sinti's recession curve makes the short- to long-time transition on March 6 and Tinubdan on March 8. It is interesting that these dates do not coincide more closely. Presumably, large watersheds experience periods in which some parts are experiencing short-time behavior while others are behaving with long-time characteristics. This heterogeneity in flow behavior across a watershed likely contributes to the scatter in the data as presented for the type of recession analysis carried-out in this study (Figs. 3–5 and 7) [4,6,16]. The linear reservoir ($b = 1$) and Brutsaert ($b = 1.5$) solutions arise from slightly different expressions or simplifications of the Boussinesq Equation. However, for this type of recession flow analysis, the degree of heterogeneity in watershed-wide flow behavior may influence which solution best fits the long-time recession behavior as much as which mathematical expression best describes the watershed's hydraulics.

Fig. 7 shows the recession flow analysis for combined flows from all the springs. Both the linear reservoir and Brutsaert solutions have been superimposed on the data and it is difficult to determine which best describes the recession flow behavior for these springs. The similarity of flow half-lives among the different springs suggests that this watershed is relatively homogenous. Note that all three envelopes in Fig. 7, the short-time, linear reservoir, and Brutsaert solutions, all overlap within a small area of the graph. This was found to be true of the individual springs as well (data not shown) and suggests that locating the transition between short- and long-time flow was relatively insensitive to the long-time solution chosen. The flow half-life calculated using the combined flows was 29 days, which is in the same range as the other analyses. This is in agreement with findings of Szilagyi et al. [15] who used numerically generated recession flows to show that increasing complexity of the aquifer had no impact on the accuracy of the estimated parameters.

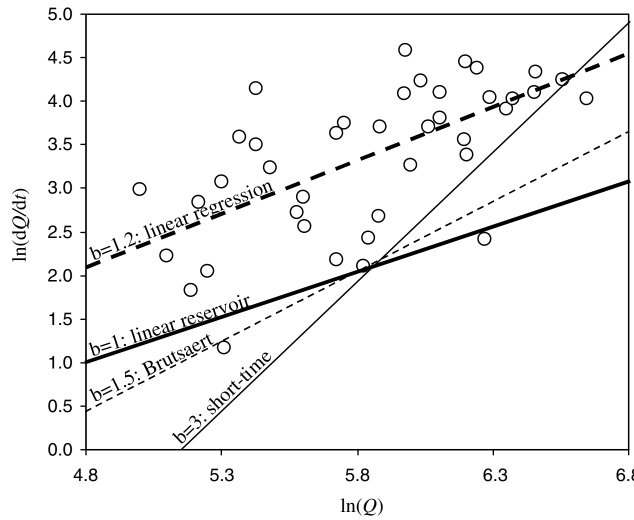

Fig. 7. ln(dQ/dt) vs. ln(Q) for the combined flow from all of the observed springs. The lines show different approaches to determining envelopes for recession flow behavior.

Finally, the analysis shows that the combined flows is over-whelmed by the outflow of the larger aquifers. Thus, the hydraulic parameters that can be determined, Eq. (5), represent the larger aquifers and not the smaller ones. Consequently, for the analysis of Brutsaert and Nieber [6], the parameter values likely represent the soils in the valley bottom and not the majority of the (shallow) soils on the hillsides. This explains then, also, the high values of the conductivity of the soil found by them because these valley bottoms have gravelly soils and a high conductivity.

6. Conclusion

This study demonstrated the utility of stream baseflow recession analyses to spring drought flow. Two solutions to the long-time recession behavior were investigated and it was unclear that either was consistently better at describing the flow behavior. Using the linear reservoir solution, flow half-life was determined for springs. The small springs were generally characterized with flow half-lives of about a month and the large springs had half-lives of 0.5–1 month. The flow half-life is the duration, in the absence of groundwater recharge, required for the springs' discharge to decrease by a factor of two. This type of analysis provides a simple evaluation of the potential for spring development as a water source.

This study also confirms the validity of using the recession flow analysis proposed by Brutsaert and Nieber [6] and subsequently modified by Brutsaert and various of his colleagues by demonstrating that the recession flow behavior of a whole watershed is similar to that of individual sub-basins. This explains why a theory mathematically developed using simple basin geometry has been shown to work well despite complicated basin geometry.

Acknowledgement

The authors thank Mahima Walter for her assistance in preparing the figures for this paper.

References

[1] Boussinesq J. Sur le débit en temps de sécheresse d'une source alimentée par une nappe d'eaux d'infiltration. CR Hebd Sé-ances Acad Sci 1903;136:1511–7.

[2] Boussinesq J. Recherches théoriques sur l'écoulement des nappes d'eau infiltrées dans le sol et sur le débit des sources. J Math Pures Appl 5me Sér 1904;10:5–78.

[3] Brutsaert W. The unit response of groundwater outflow from a hillslope. Water Resour Res 1994;30(10):2759–63.

[4] Brutsaert W, Lopez JP. Basin-scale geohydrologic drought flow features of riparian aquifers in the southern Great Plains. Water Resour Res 1998;34(2):233–40.

[5] Brutsaert W, Lopez JP. Reply to Comment on "Basin-scale geohydrologic drought flow features of riparian aquifers in the southern Great Plains". Water Resour Res 1999;35(3):911.

[6] Brutsaert W, Nieber JL. Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res 1977; 13(3):637–43.

[7] Chandler DG, Walter MF. Runoff responses among common land uses in the uplands of Matalom, Leyte, Philippines. Trans ASAE 1998;41(6):1635–41.

[8] Dayot A, Diokno E, Tomas L, Villamayor F, Villanueva R. Semi-detailed soil survey of some barangays of Matalom Leyte Philippines. Ithaca, NY: Department of International Agriculture Report, Cornell University; 1998.

[9] Fair D. Water and sanitation in sub-Saharan Africa: serving the rural poor. Africa Insight 1995;25(1):48–53.

[10] Godilano EC. Spatial analysis framework for community-based watershed management in tropical uplands of the Philippines. PhD thesis, Cornell University, Ithaca, NY. 1998.

[11] Malvicini C. Drinking water quality and reliability: an assessment of the springs in the Philippine uplands. MS thesis, Cornell University, Ithaca, NY. 2000.

[12] Mendoza G, Steenhuis TS, Walter MT, Parlange J-Y. Estimating basin-wide hydraulic parameters of a semi-arid mountainous watershed by recession-flow analysis. J Hydrol 2003;279:57–69.

[13] Michel C. Comment on "Basin-scale geohydrologic drought flow features of riparian aquifers in the southern Great Plains". Water Resour Res 1999;35(3):909–10.

[14] Parlange J-Y, Stagnitti F, Heilig A, Szilagyi J, Parlange MB, Steenhuis TS, et al. Sudden drawdown and drainage of a horizontal aquifer. Water Resour Res 2001;37(8):2097–101.

[15] Szilagyi J, Parlange MB, Albertson JD. Recession flow analysis for aquifer parameter determination. Water Resour Res 1998; 34(7):1851–7.

[16] Troch PA, DeTroch FP, Brutsaert W. Effective water table depth to describe initial conditions prior to storm rainfall in humid regions. Water Resour Res 1993;29(2):427–34.

[17] Tucker T. Informal farmer experimentation in resource-poor environments: a study of differential propensity and capacity. PhD thesis, Cornell University, Ithaca, NY. 1998.

[18] Zecharias YB, Brutsaert W. Ground surface slope as a basin scale parameter. Water Resour Res 1985;21:1895–902.

[19] Zecharias YB, Brutsaert W. Recession characteristics of groundwater outflow and base-flow from mountainous watersheds. Water Resour Res 1998;24:1651–8.