Rainfall-Discharge Relationships for a Monsoonal Climate in the Ethiopian Highlands

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Abstract

This study presents a simple rainfall-discharge analysis for the Andit Tid, Anjeni, and Maybar watersheds of northern Ethiopia. The Soil Conservation Research Programme (SCRP) established monitoring stations in each of these sites during the 1980's, with climate and stream flow measurements being recorded up to the present. To show how these data could be used to provide insight into catchment-level runoff mechanisms, simple linear relationships between effective precipitation and runoff are developed for each watershed, with the conclusion that all three watersheds exhibit consistent hydrologic behavior after approximately 500 mm of cumulative effective seasonal rainfall has fallen since the beginning of the rain season. After the 500 mm rainfall threshold has occurred, approximately 50% of any further precipitation on these watersheds will directly contribute to catchment runoff.

Introduction

The amount and quality of hydrologic data collected in Africa are rapidly growing, with the appropriate organization and analysis of these data becoming especially important towards gaining real benefits from many projects. In Ethiopia engineering solutions such as the Rational Method have been utilized (Desta, 2003), but despite the lack of advanced technical resources, complex, established models have been applied such as the Precipitation Runoff Modeling System (PRMS) (Legesse et al., 2003), Water Erosion Prediction Project (WEPP) (Zeleke, 2000) or the agricultural non-point source (AGNPS) pollution model (Mohammed et al., 2004). These models and methods have been developed for temperate climates, and may not apply to the monsoonal climates of Africa with a distinct dry season where the soil dries out to considerable depth. Moreover all of these models that are used in Ethiopia are based on the assumption that runoff is created by infiltration excess processes where runoff occurs when the precipitation rate exceeds the infiltration capacity of the soil. Infiltration measurements and plot studies in Ethiopia have shown, however, that the infiltration rates, especially on hillsides with stone cover, can be of the same order of magnitude or higher than the greatest rainfall intensity (McHugh, 2006). Thus, although infiltration excess can occur, the most likely mechanism that produces the majority of the runoff is saturation excess in which the shallow soil becomes saturated (either from the rainfall or from interflow from upslope areas) and produces runoff. Methods that are less dependent on the type of runoff focus on water balances (e.g., Johnson and Curtis, 1994; Conway, 1997; Kebede et al. 2006; and Mishra and Hata, 2006) and may prove to be a more robust and parsimonious solution to the problem. Zeleke (2000) stated that discrepancies in WEPP model predictions were caused by the inability of the model to predict saturation-excess runoff. It is surprising, therefore, that saturation excess models such as TOPMODEL (Beven et al. 1984) and SMDR (Easton et al. 2007) have not yet been applied in the Ethiopian context,

Knowledge of the basic runoff mechanisms is necessary before an appropriate model formulation can be selected. To derive these mechanisms, we use a water balance method employing existing data in three small watersheds and then use the outcome of these water balance calculations to suggest runoff mechanisms that may explain the observed pattern.

Methods

The Soil Conservation Research Programme (SCRP) was an extensive project implemented from 1981-1998 to help understand land degradation processes and generate imperical evidences to combat land degradation in Ethiopia. It was administered by the Ethiopian government, primarily the Ministry of Agriculture, and the Center for Development and Environment (CDE) of Bern University. The project was funded by Swiss Agency for Development and Cooperation (SDC).

Through this project seven research sites were established around the country to generate data on land degradation (soil loss, runoff, catchment discharge, etc.) and field test soil conservation methods and collect baseline data. An impressive database of information has been built, with the intention of continued data collection after the project ended. This study uses hydrologic data collected from the three research stations in the Amhara National Regional State: Andit Tid, Anjeni, and Maybar (Fig. 1). All three sites are agricultural lands with extensive soil erosion control structures built to assist the rain-fed subsistence farming, but the watersheds differ in size, topographic relief, and climate (Table 1).

SCRP trained local research assistants in each respective watershed to collect data continuously. Rainfall was measured with automatic pluviographs and daily evaporation was measured with screened Piche evaporameters. Daily maximum and minimum temperatures were measured in the air (1.5 m above ground) and the soil surface (0.1 m above ground) along with manual rain gauge readings. Stream flow discharge from each catchment was determined from automatic float gauges combined with manual stage readings. Further information on the initial data collection and processing can be found in Hurni (1984) and Bosshart (1997a).

Many of the daily potential evaporation measurements during the dry months were quite high, sometimes over 10 mm/day. These were affected by the dry landscape surrounding the measurement sites (Brutsaert, 2005) and did not seem reasonable for these mountainous locations. Allen et al. (1998) calculated Penman-Monteith potential evapotranspiration (E) rates for a reference crop in each of the three watersheds. Maximum calculated E values for Andit Tid, Anjeni, and Maybar were 5.0 mm/day, 7.6 mm/day, and 6.9 mm/day, respectively. Consequently, a 7 mm/day ceiling was applied to all potential evaporation values before further analysis.

Daily rainfall, evaporation, and discharge data were summed over weekly, biweekly and monthly periods to find the most appropriate representation of watershed behavior. For most analyses, precipitation minus evaporation *(P-E)* was used instead of just precipitation since we found that the combined value was a more accurate estimate of the water available for movement or storage in the soil. In addition, to study the effect of watershed moisture status, cumulative rainfall during each season was calculated. Since the start and ending of the rain season varies in the highlands of Ethiopia, a simple but consistent method to delineate seasons had to be developed. Instrumenting the deep Haplic Phaezem soils found in Maybar, Bono and Seiler (1987) found that 9-10 rainless days dried out a wet soil to a depth of 10 cm, and 28-29 days dried out the soil to 50 cm. Thus the following algorithm was developed for delineating seasons: if the number of days with P-$E > 0$ within the last 30-day period was greater than or equal to 10 and the 30-day sum was positive, then the "rain season" was initiated. If none of the days within the previous 14-day period had rainfall in excess of potential evapotranspiration (i.e., $(P$-$E) > 0$) then the rain season was stopped. The "dry season" was defined as the remaining part of the year.

Results

Temporal dynamics were found to play an important role in the hydrologic behavior of the watersheds. Plots of daily rainfall and runoff values were not particularly well correlated. In conjunction with the short and sometimes intense rainstorms found in this region at the beginning of the rain season, all three watersheds typically produced runoff immediately after a large storm. However, as shown in Fig. 2, less intense storms at the end of rain season could also create more extended periods of runoff. Using daily values gave misleading relationships in these cases because the interflow was not included.

Thus, we determined that weekly sums were most suitable for producing overview hydrographs (Fig. 3) that retained the influence of peaks from individual storms but also clearly conveyed when watersheds were in water deficit and when they became saturated and subsequently produced rapid runoff responses. When looking for rainfall-discharge relationships, longer time periods were required to capture the stream responses in order to include the interflow component. Both biweekly and monthly summations were able to adequately show this, but biweekly divisions resulted in twice as many points so were selected for comparison analyses.

Andit Tid, the largest study site, was also the highest and least populated. Hill slopes were very steep and degraded, resulting in 54% of the long-term precipitation becoming runoff. Despite its larger size, stream flow quickly returned to nearly zero during the typically dry months of November through March. During the larger *kremt* wet season, normally June through October, after a few storms wet the soils, most of the effective rainfall *(P-E)* became runoff (Fig. 3a). However, stream discharges did not immediately return to dry season levels, instead they steadily decreased (e.g., October-December 1995 in Fig. 3a).

Anjeni, located in one of the country's more productive agricultural areas, was the lowest in elevation and highest in population density. This site receives more rain than the other two and has only one rain season, typically May through October. In similar fashion to Andit Tid, the Anjeni watershed required only a few storms at the beginning of each wet season to satisfy the watershed storage and begin producing runoff (Fig. 3b). Unlike Andit Tid, where discharge peaks often overlapped the effective precipitation peaks, at Anjeni the discharges were a smaller proportion of the *(P-E)*, and only 43% of the long-term rainfall ended up at the watershed outlet (Table 1). Some possible explanations for the observed difference could be slope type (which is gentle in Anjeni), soil type (better infiltration capacity and in some cases deep) and most importantly, the Anjeni watershed is well treated by physical soil and water conservation measures.

Finally, Maybar behaved in a similar manner to Anjeni except for the difference in rain season patterns (Fig. 3c). Thirty-four percent of the long-term precipitation in Maybar became discharge at the outlet.

To further investigate runoff response patterns, the biweekly sums of discharge were plotted as a function of effective rainfall (i.e., *P-E* for a two week period) during the rain season and dry season (as defined earlier) in Fig. 4. As is clear from Fig. 3, Fig. 4 shows that the watershed behavior changes as the wet season progresses, with precipitation later in the season generally producing a greater percentage of runoff. As rainfall continues to accumulate during a rain season, each watershed eventually reaches a threshold point where runoff response can be predicted by a linear relationship with effective precipitation, indicating that the proportion of the rainfall that became runoff was constant during the remainder of the rain season. For the purpose of this study, an approximate threshold of 500 mm of effective cumulative rainfall, *P-E*, was selected after iteratively examining rainfall vs. runoff plots for each watershed. The proportion Q/(P-E) varies within a relative small range for the three watersheds. In Andit Tid approximately 56% of late season effective rainfall, *P-E*, became runoff (Table 2), while ratios for Anjeni and Maybar were 48% and 50%, respectively. There was no correlation between biweekly rainfall and discharge during the dry seasons at any of the sites.

Since each of the study sites showed a similar linear response after the threshold cumulative rain was satisfied, the latter parts of the wet seasons were all plotted in the same graph (Fig. 5). Despite the great distances between the watersheds and the different characteristics, the response was surprisingly similar. The Anjeni and Maybar watersheds had almost the same runoff characteristics, while Andit Tid had more variation in the runoff amounts but on average the same linear response with a higher intercept (Fig. 5). Linear regressions were generated for both the combined results of all three watersheds and for the Anjeni and Maybar watersheds in combination with the combined Anjeni and Maybar watershed regression having less correlation (r^2 = 0.61 compared with 0.80). The regression slope does not change significantly, but this is due to the more similar Anjeni and Maybar values dominating the fit (Table 2). Note that these regressions are only valid for the end of rain seasons when the watersheds are wet.

Discussion

Why these watersheds behave so similarly after the threshold rainfall has fallen is an interesting question to explore. It is imperative, therefore, to look at various time scales, since focusing on just one type of visual analysis can lead to erroneous conclusions. For example, looking only at storm hydrographs of the rapid runoff responses prevalent in the typically intense Ethiopian storms, one could conclude that infiltration excess is the primary runoff generating mechanism. However, looking at longer time scales in Figs. 3 and 4 it can be seen that the ratio of $Q/(P\text{-}E)$ is increasing with cumulative precipitation and consequently the watersheds behave differently depending on how much moisture is stored in the watershed, suggesting that saturation excess processes play an important role in watershed response. If infiltration excess was controlling runoff responses, discharge would only depend on the rate of rainfall, and there would be no clear relationship with antecedent precipitation, as is clearly the case looking at Figs. 3 and 4.

Next, we will attempt to show that the saturation excess mechanism, despite the different rainfall patterns between the three watersheds, is the main reason that the runoff behavior is similar. Previously we have shown that the ratio of direct runoff to precipitation for a particular storm can be used to derive the portion of area in the watershed that contributes the direct runoff to the outlet (Steenhuis et al., 1995). The area of the watershed that produces runoff is called the contributing area or variable source area. Because of the 14 day observation period used in the three watersheds, not only direct runoff but also the base flow and interflow are included in the watershed discharge, and is at times is not a minor component. Schum (2004) found that half of the Anjeni catchment's discharge was derived from base and interflow. This means that the contributing area is larger than when only direct runoff is considered. Moreover, since water is lost by evaporation during this period, *P-E* is a better measure of the amount of water that is available for runoff than *P* by itself. Based on this we can set the portion of the area contributing over the 14 day period equal to the ratio of the *Q/(P-E)*, where *Q* includes direct storm runoff, interflow and baseflow.

Accordingly as the ratio of *Q* to *P-E* increases during the rain season as seen in Fig. 4, the contributing area must increase as a function of the cumulative rainfall. This is most distinctly shown for the Anjeni watershed (Fig. 4b) which has the clearest signal likely because the rainfall distribution is unimodal (Table 1). The first 100 mm of (cumulative) rainfall all infiltrates and none of the watershed is contributing. The little runoff that occurs in few cases (as well as during the dry season) is either from small patches of permanently saturated soils or Hortonian flow (e.g., infiltration excess). For runoff events that occur when there is 100-300 mm of cumulative rainfall the ratio of *Q* and *P-E* is 0.20 indicating that 20% of the watershed is contributing. The transition from no contributing area to 20% seems to be rather sudden, an indication that 20% of the watershed has a storage capacity of approximately 100 mm. For P-E between 300 -500 mm there is a cloud of points through which it is difficult to draw a line indicating that it is a transition period in which the contributing area increases gradually with cumulative precipitation in some areas but not in others. Finally, for cumulative rainfall amounts larger than 500 mm the contributing area does not change anymore and nearly 50 % of the area contributes runoff through the remainder of the season.

Maybar in Fig. 4c behaves similar to Anjeni, but has more variability in runoff amounts. The Andit Tid watershed in Fig. 4a has the greatest variability in runoff amounts. This watershed is larger and the ground water component (i.e., baseflow) is likely a larger component as ground water contribution increases with watershed size. The variability in rainfall is also the largest with significant rains occurring in the “dry period” that occur at a time when the watershed is still partly saturated. Some other differences between the watershed behaviors are likely due to the *belg* rain season in Ethiopia. This smaller rain season occurs erratically between January and May and is especially variable at Maybar. Sometimes the *belg* brought precipitation levels equal to those found in the longer *kremt* season (as in April-May 1995, Fig. 3c) and sometimes it brought very little. Everson (2001) found that stream flow in grasslands in the mountains of South Africa depended more on the distribution of rainfall than or the annual volume, so unpredictable *belg* rains could have a similarly important influence in Ethiopia.

Thus, the watersheds’ runoff flows behave similarly and linearly with *(P-E)* after the rainfall threshold is satisfied because the area that contributes runoff remains the same independent of the amount of rainfall. Physically we can see these runoff contributing areas in the landscape as the low lying grass covered sections between the agricultural fields. There is a sharp and uniform demarcation line. These areas are too wet for growing crops. It is likely that parts of the hillsides are also contributing as interflow. Flows in the drainage ditches on the hillsides after runoff has left the watershed often suggest this.

The finding that saturation excess is occurring in watersheds with a monsoonal climate is not unique. For example, Hu et al. (2005), Lange et al. (2003), and Merz et al. (2006) found that saturation excess could describe the flow in a monsoonal climate in China, Spain, and Nepal respectively. There are no previous observations published for Ethiopia on the suitability of these saturation excess models to predict runoff even though attempts to fit regular models based on infiltration excess principles result extremely poor fits (Haregeweyn et al., 2003, Zeleke, 2000). This is not to say that infiltration excess overland flow does not exist at all. Both types could occur during particularly high intensity storms. However, as shown by van de Giesen et al. (2000) in the Ivory Coast, a large portion of the overland flow re-infiltrated after the rain stopped before reaching the channel.

Looking at the remaining parts of the watershed that do not directly contribute to runoff, these soils likely are deeper or have a higher infiltration rate through the hard pan allowing more unrestricted drainage. Part of the water in these non-contributing areas becomes deep, regional groundwater that is not recorded by the local gages, and may appear downstream of these small watersheds at larger gages. Andit Tid, which has both the largest watershed and contributing area, intercepted more of this deep, regional groundwater.

Results from this study should be validated on other sites as data become available, but perhaps the following generalizations could be used as a first estimate when discharge measurements are not available for similar watersheds in Amhara: for cumulative rainfall up to 100 mm the rain all infiltrates; for cumulative rainfall from 110 to 300 mm approximately 20% of the watershed area contributes; and for cumulative rainfall above 500 mm approximately 50% of the effective precipitation becomes runoff. Note that most runoff occurs later in the season during an important time of crop growth, so relatively simple analyses like this could be useful in estimating available water and by extension seasonal yields.

Of course, such generalizations must be used cautiously since runoff mechanisms are dependent on a multitude of factors. Andit Tid, being more than four times as large as the other sites, displayed a wider range of runoff responses to individual storm events depending on the time of year. This size advantage conversely allowed Andit Tid to account for a much greater percentage of rainfall since a larger fraction of water likely circumvents the stream gauge in the smaller watersheds.

Conclusions

Rainfall-runoff relationships in three small watersheds with more than 10 years of record were analyzed. Each of the watersheds has a limited amount of storage, with certain confluence areas quickly becoming saturated and directly contributing runoff with additional rainfall. Eventually, as the rain season continues, any areas of the landscape that have the potential to contribute runoff become wet enough that this fixed percentage of each watershed produces rapid flow in any later events. For the three watersheds in this study, the point at which potential runoff sites consistently become active occurs after approximately 500 mm of cumulative effective rainfall has fallen and the potential runoff contributing area represents nearly 50% of the watershed area

Water balance methods such as the one presented in this study are relatively easy to perform yet can produce needed insight into the water transport process that occurs in the remote highlands of Ethiopia. It is of interest to apply this method to other monsoonal climates to understand if our observations apply to other areas in the world as well.

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Figure 5. Biweekly summed effective rainfall/discharge relationships for all three watersheds but only during the latter part of the rain seasons, after 500 m of cumulative rainfall *(P-E)* has fallen. Linear regressions are provided for the combined plots: all three together are shown with a solid line and only Anjeni and Maybar (together) are shown with a dotted line.

Table 1. Overview of the three SCRP watersheds

	Andit Tid†	**Anjeni‡**	**Maybar††**
Area (ha)	477.3	113.4	112.8
Elevation range (m)	3040-3548	2407-2507	2530-2858
Mean annual temp (°C)	12.6	16	16.4
Mean annual rainfall (mm)	1467	1675	1417
Mean annual evap (mm)	1174	1400	1147
Rainfall pattern	Bimodal	unimodal	bimodal
Growing season (days)	175	242	175
Population (persons/km^2)	146	193	188
Primary crops	barley	barley, cereals, beans and oils	cereals, maize
Major soils	Andosols, Fluvisols, Regosols, Lithosols	Alisols, Nitosols, Cambisols	Phaeozems, Lithosols, Gleysols
Years of data available	12	10	11
Long-term *Q/P* ratio	0.54	0.43	0.32

†(SCRP, 2000a)
‡(SCRP, 2000b)
††(SCRP, 2001)

Table 2. Summary of linear rainfall-discharge relationships found during latter part of the rain season.

Watershed	**Figure**	**Cumulative *(P-E)* threshold**[a]	**Slope**[b]	**Intercept**[b] **(mm)**	$\mathbf{r^2}$
Andit Tid	4a	~500 mm	0.56	38	0.50
Anjeni	4b	~500 mm	0.48	16	0.83
Maybar	4c	~500 mm	0.50	13	0.75
All three combined	5	~500 mm	0.56	40	0.61
Anjeni & Maybar together	5	~500 mm	0.49	14	0.80

[a] The amount of cumulative rainfall in a season after which the watershed responds in a consistent fashion

[b] Relationships here are for biweekly summations of (P-E) and Q

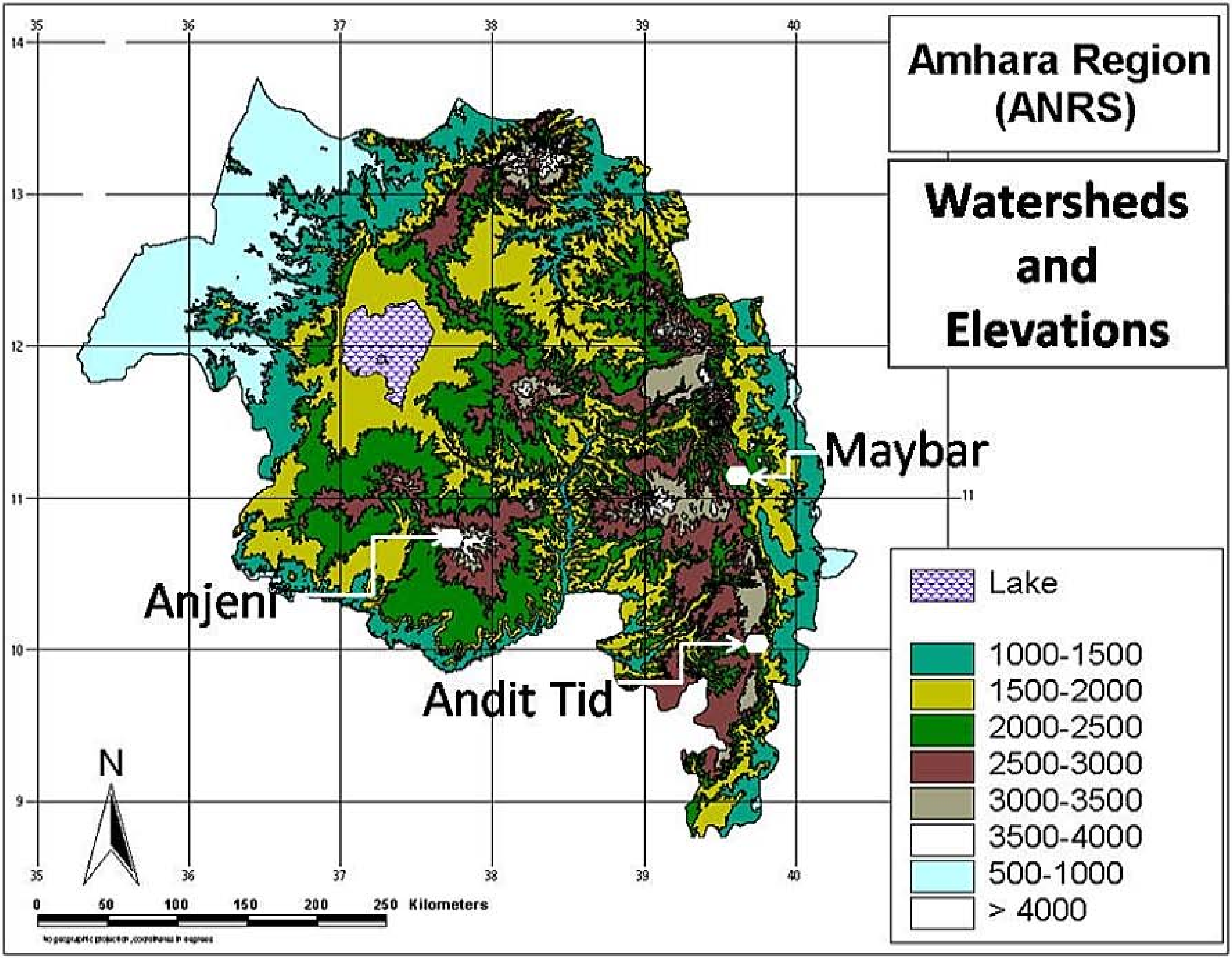
Amhara Region (ANRS)
Watersheds and Elevations
Maybar
Anjeni
Andit Tid
N
Lake
1000-1500
1500-2000
2000-2500
2500-3000
3000-3500
3500-4000
500-1000
> 4000
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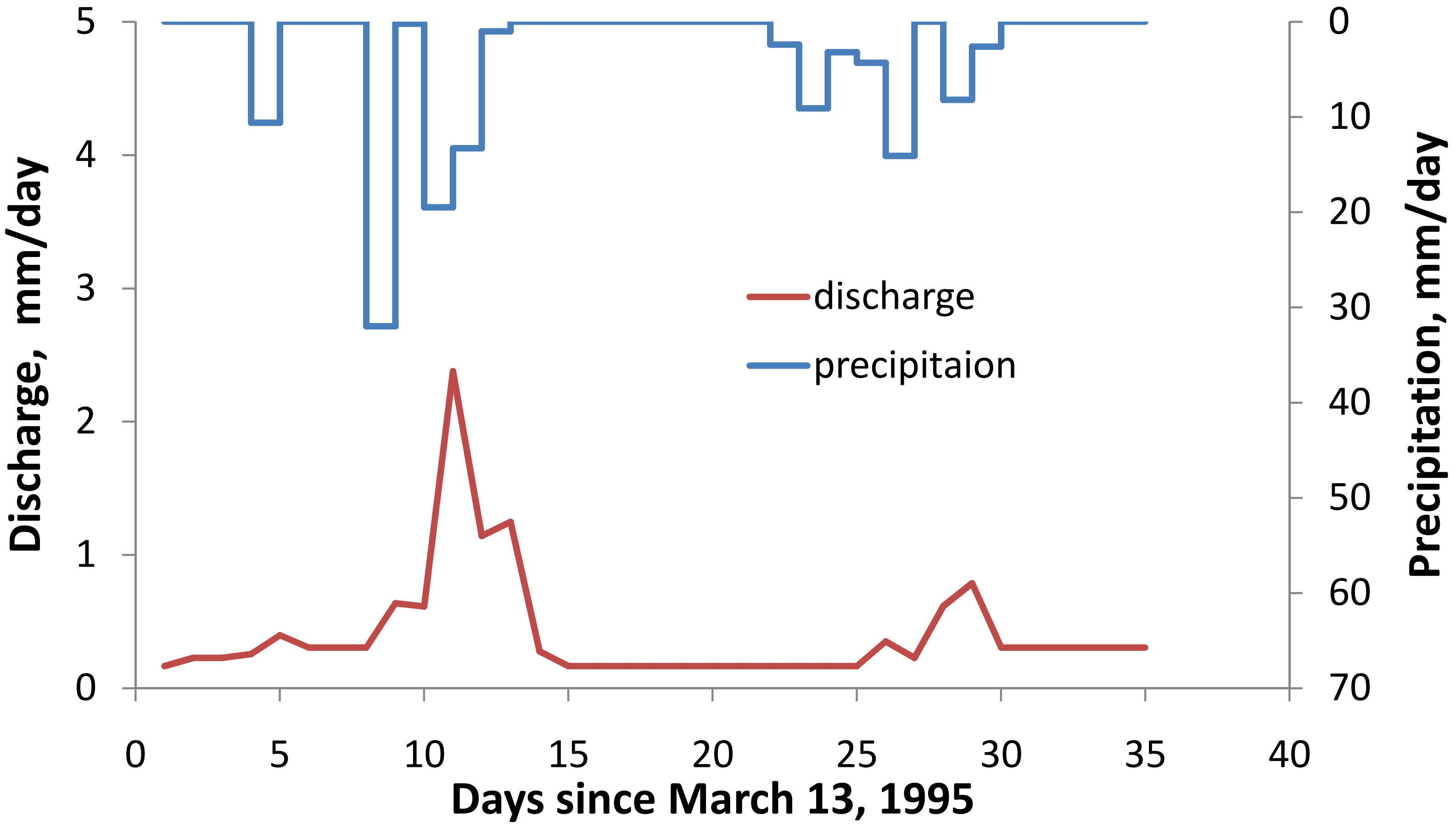
figure 1


5
4
3
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Discharge, mm/day
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10
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Precipitation, mm/day
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30
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40
Days since March 13, 1995
discharge
precipitaion

Figure 2a

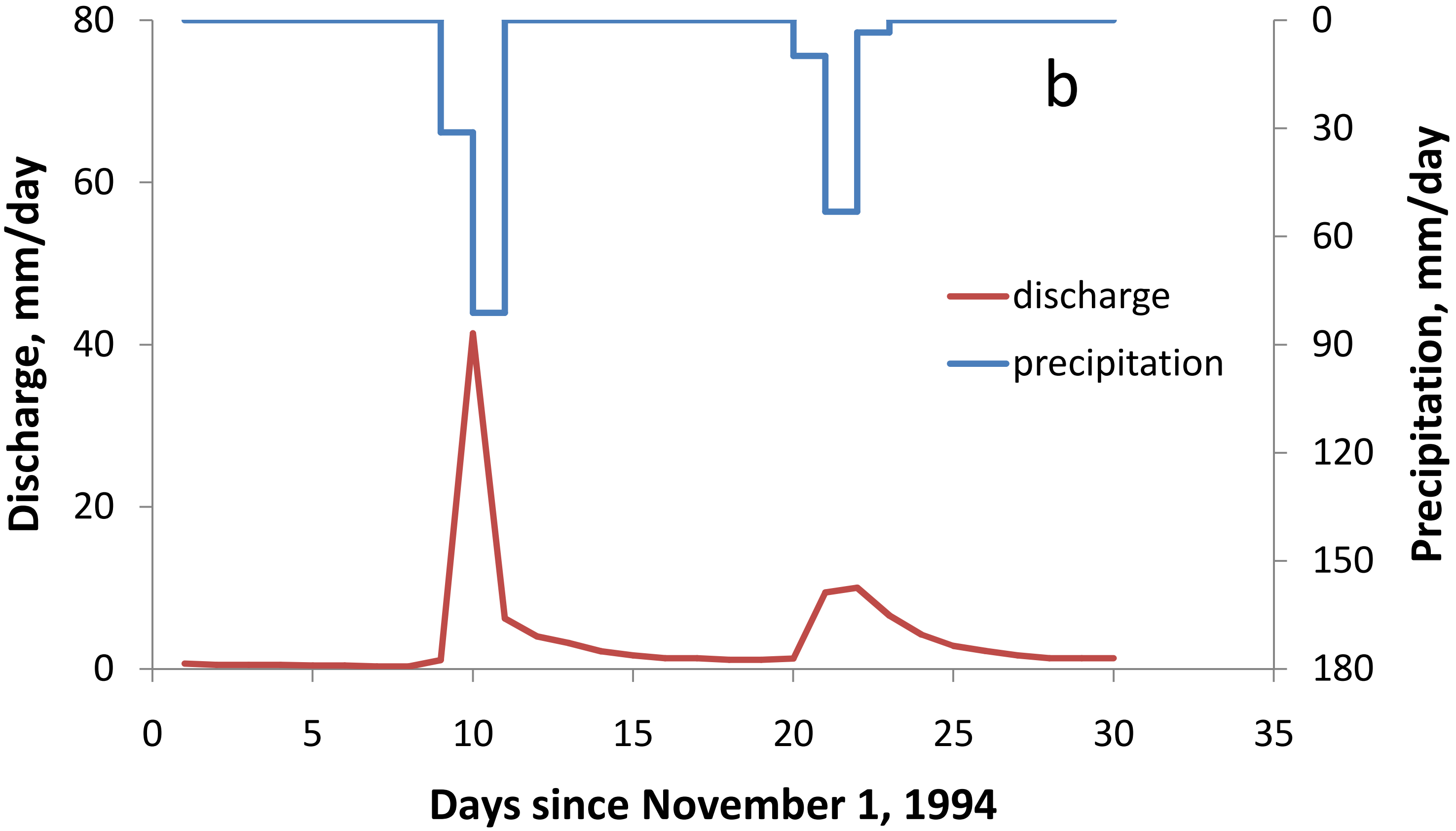
b
Discharge, mm/day
0
20
40
60
80
Precipitation, mm/day
0
30
60
90
120
150
180
0
5
10
15
20
25
30
35
Days since November 1, 1994
discharge
precipitation

figure 2b

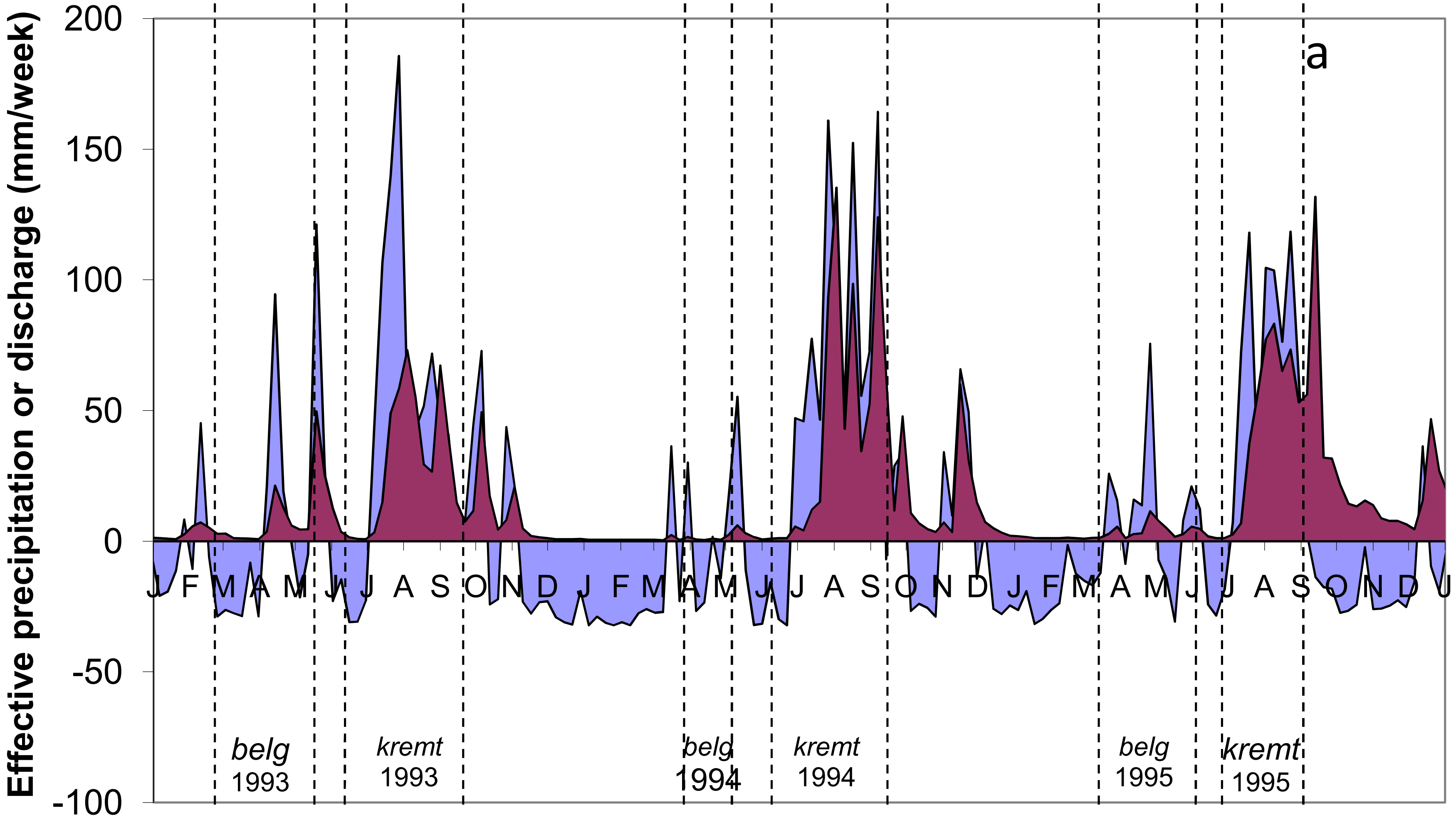
Effective precipitation or discharge (mm/week)
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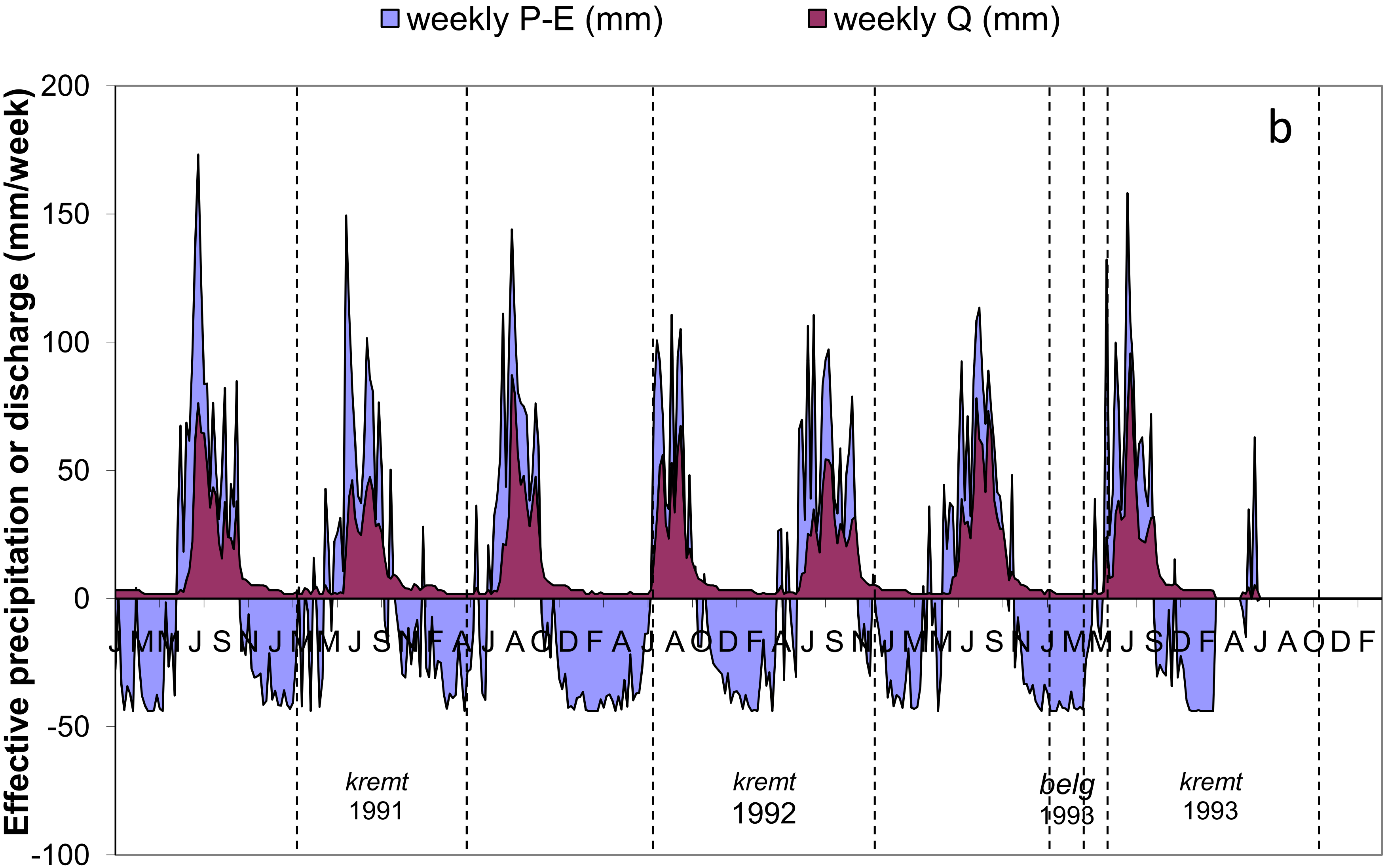
figure 3a



weekly P-E (mm)
weekly Q (mm)
Effective precipitation or discharge (mm/week)
200
150
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50
0
-50
-100
b
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1993

figure 3b

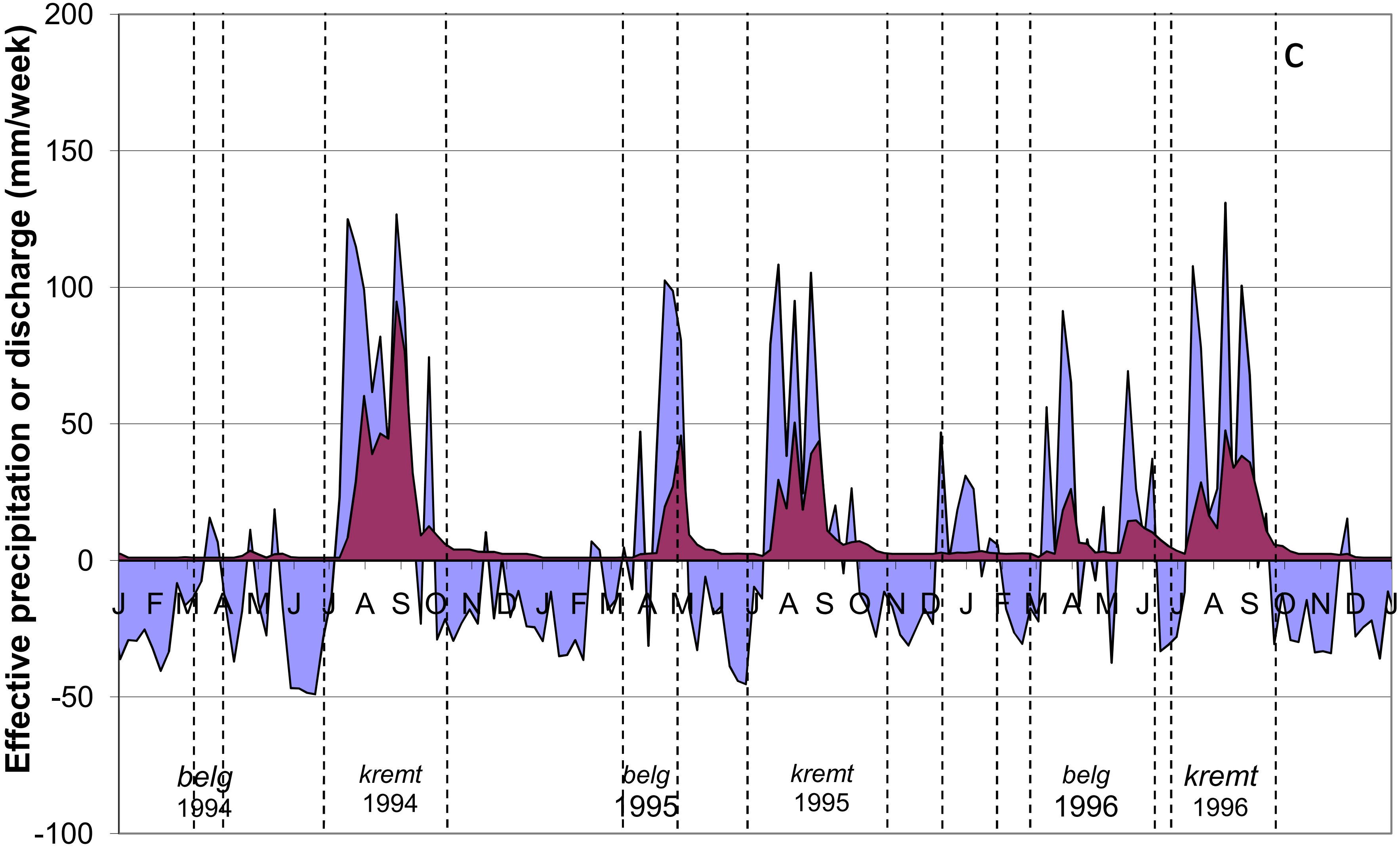

Effective precipitation or discharge (mm/week)
200
150
100
50
0
-50
-100
c
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J
belg 1994
kremt 1994
belg 1995
kremt 1995
belg 1996
kremt 1996

figure 3c

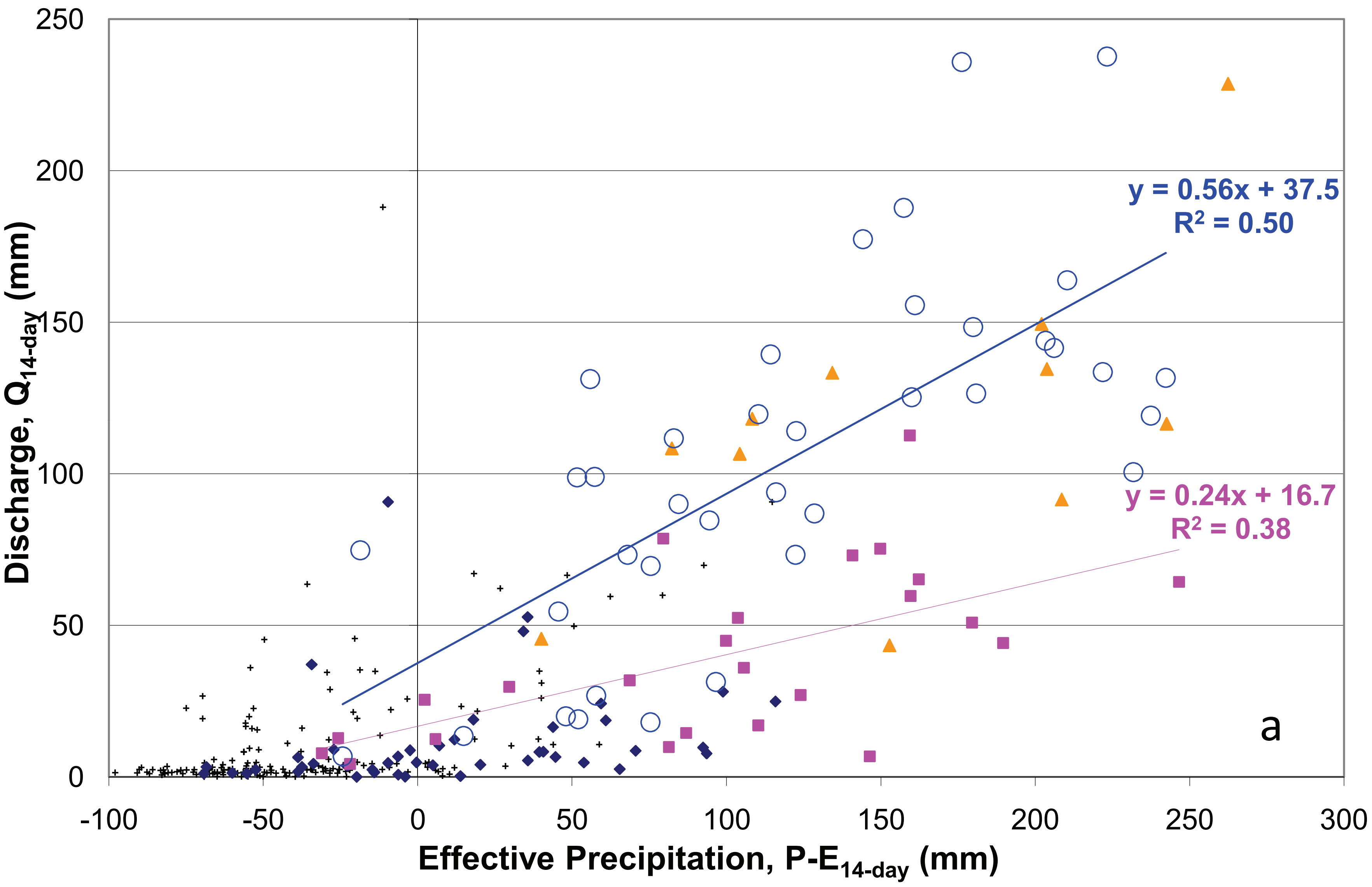

y = 0.56x + 37.5
R² = 0.50
y = 0.24x + 16.7
R² = 0.38
a
Discharge, Q14-day (mm)
250
200
150
100
50
0
Effective Precipitation, P-E14-day (mm)
-100
-50
0
50
100
150
200
250
300

figure 4a

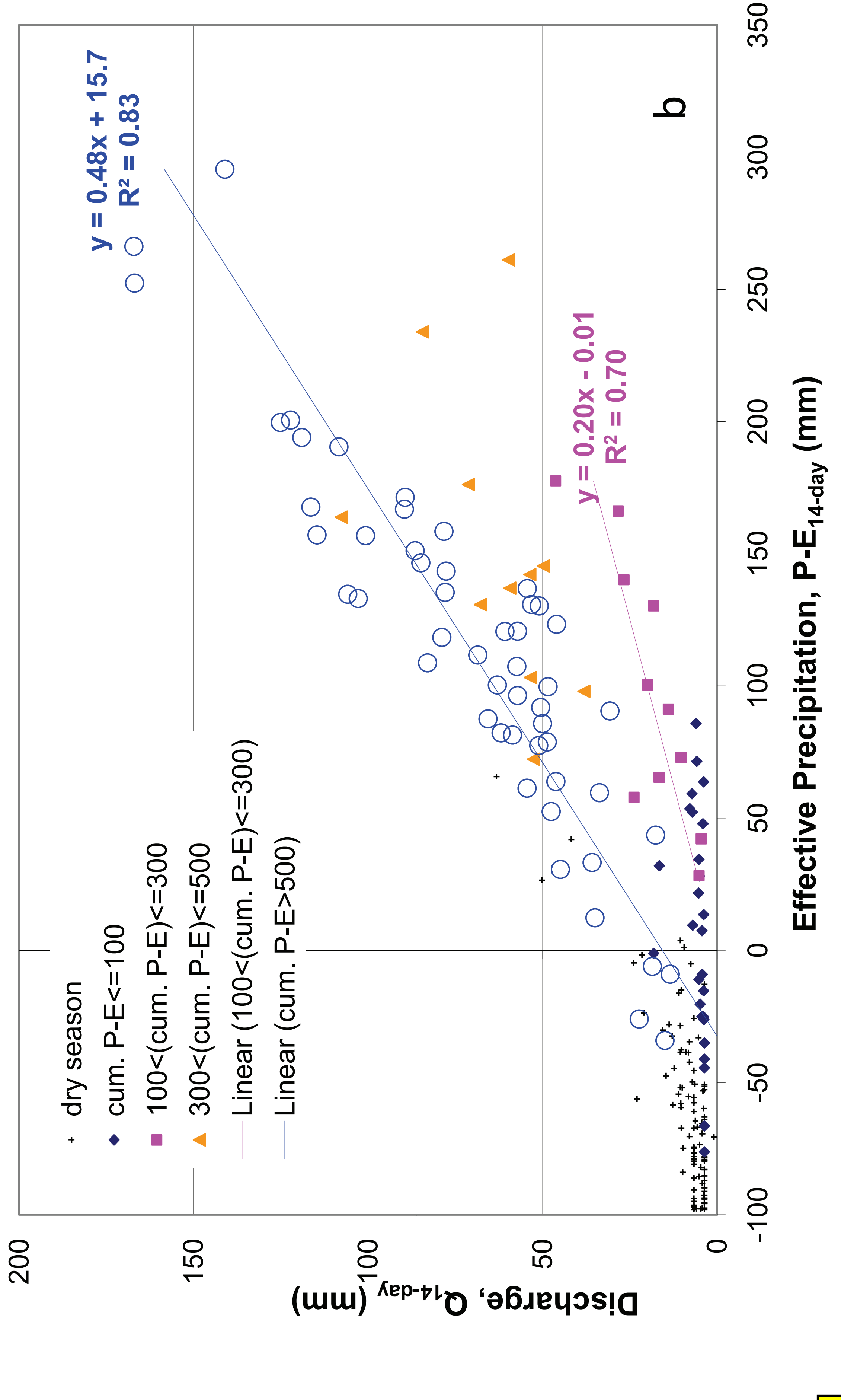
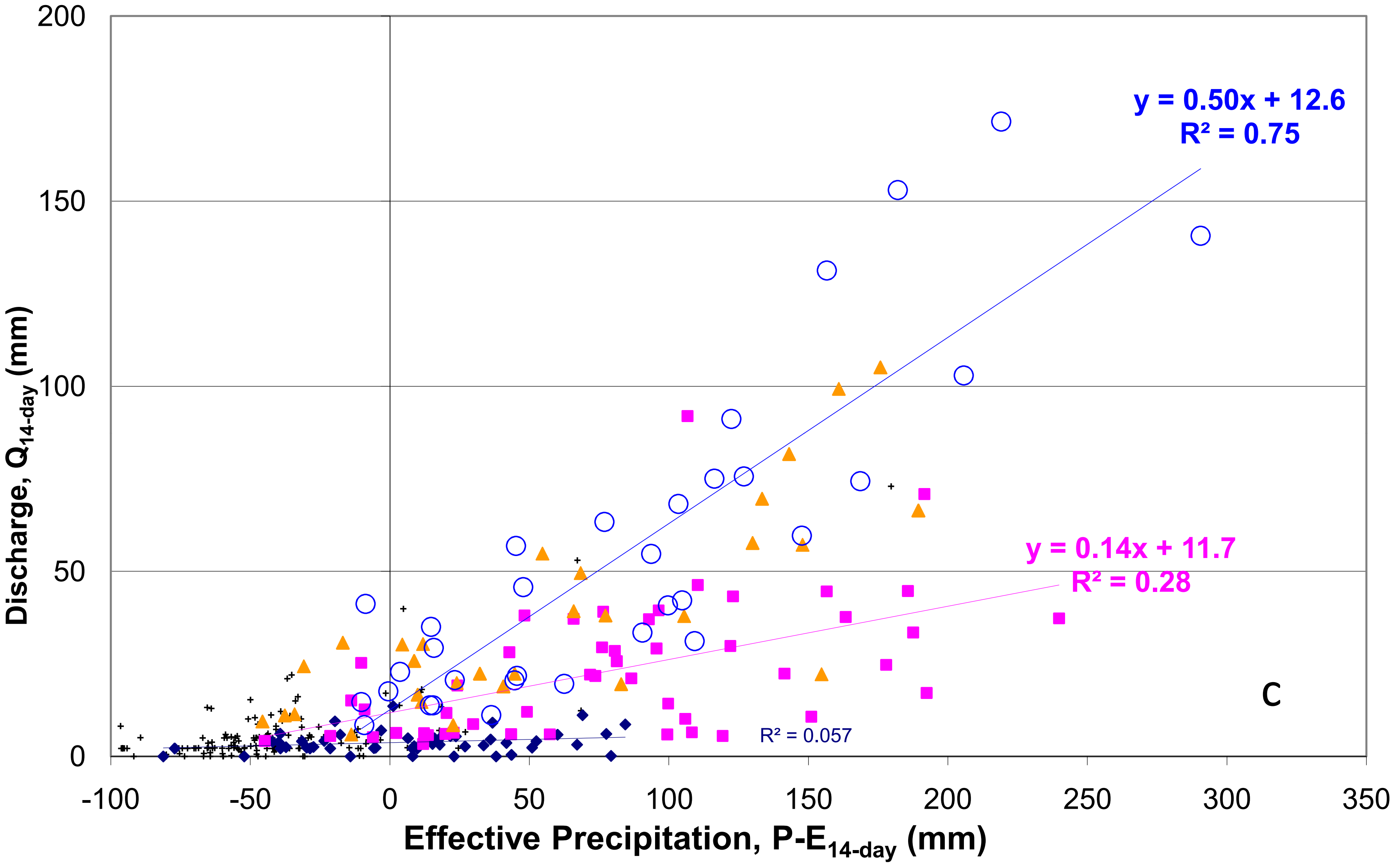
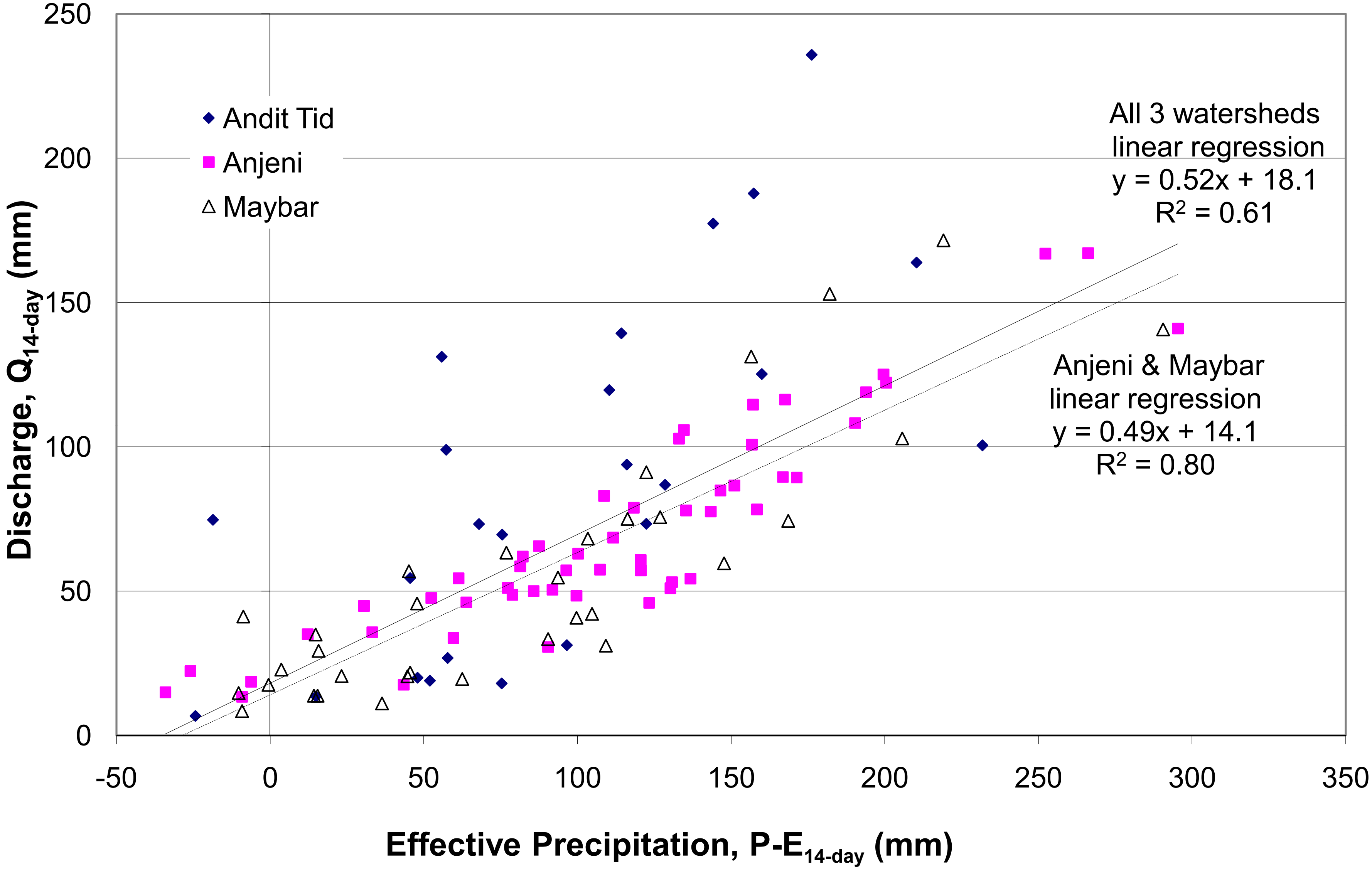

b
dry season
cum. P-E<=100
100<(cum. P-E)<=300
300<(cum. P-E)<=500
Linear (100<(cum. P-E)<=300)
Linear (cum. P-E>500)
y = 0.48x + 15.7
R² = 0.83
y = 0.20x - 0.01
R² = 0.70
Effective Precipitation, P-E14-day (mm)
Discharge, Q14-day (mm)
-100
-50
0
50
100
150
200
250
300
350
0
50
100
150
200

figure 4b



y = 0.50x + 12.6
R² = 0.75
y = 0.14x + 11.7
R² = 0.28
R² = 0.057
C
200
150
100
50
0
-100
-50
0
50
100
150
200
250
300
350
Discharge, Q14-day (mm)
Effective Precipitation, P-E14-day (mm)

Figure 4c



250
200
150
100
50
0
-50
0
50
100
150
200
250
300
350
Discharge, $Q_{14\text{-day}}$ (mm)
Effective Precipitation, P-$E_{14\text{-day}}$ (mm)
◆ Andit Tid
■ Anjeni
△ Maybar
All 3 watersheds
linear regression
y = 0.52x + 18.1
R^2 = 0.61
Anjeni & Maybar
linear regression
y = 0.49x + 14.1
R^2 = 0.80

figure 5