

## CHAPTER 4

# Groundwater discharge as affected by land use change in small catchments: A hydrologic and economic case study in Central Brazil

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### ABSTRACT

The Pipiripau river basin, a 235 km<sup>2</sup> catchment in central Brazil, has experienced a substantial increase in land use intensity (mostly agriculture and pastureland) in the last 40 years. This has contributed to a significant decrease in the base flow discharge, responsible for the maintenance of the stream flow during the dry winter season. To assess the hydrological and economic benefits of three land conservation programs in the basin, an empirical relationship was obtained between the base flow index and the normalized basin curve-number, calibrated with observed stream flow and precipitation data. The results indicate that if reforestation and best management practices are implemented in the basin, up to  $755 \times 10^6$  m<sup>3</sup>/a of additional base flow discharge would result during the dry season, with additional revenues up to US\$ 1.03 million per year for the water utility company. The simplicity of the presented methodology allows for its application in other data-scarce tropical basins.

### 4.1 INTRODUCTION

Base flow discharge is an important element of the hydrological cycle that describes the loss of water from the groundwater compartment to surface waters (GRAPHIC/UNESCO, 2006). Base flow discharge, often equalled to groundwater discharge in river basins during dry seasons, helps to maintain aquatic ecosystems and provides for important hydrological services to human communities (Tomish et al., 2004).

Groundwater discharge is influenced by climate, watershed, and land use/management conditions. Forests are an important component in the stabilization of groundwater discharge and stream flow (Pereira, 1989). When forest conversion is followed by land uses that interfere and alter natural bio-physical processes, hydrological consequences may follow (Pattanayak, 2004). Although annual and storm flows typically increase with forest conversion to agriculture, base flows often decline owing to reduced infiltration and more episodic export of water (Poff et al., 1997; Siriwardena et al., 2005).

Several studies have highlighted the impacts of land use changes to groundwater discharge in river basins. Sloto (2008) reported that a decrease of up to 63% of base flow discharge occurred following full urban build-out of a small catchment in Pennsylvania. Klöcking and Haberlandt (2002), analyzing the effect of forestation and deforestation scenarios in base flow discharge at the outlet of five German catchments, reported that base flow discharge varied from +3% to -15%, with respect to the baseline conditions.

In general, conservation practices are known to improve base flow discharge in river basins. Schilling and Libra (2003) reported that the annual base flow index increased between 20 and 30% in two catchments in Iowa in a 60-year period, following soil and water conservation projects implemented during the 1940's.

Basin scale can also affect the response of groundwater discharge to changes in land use. In small basins, the influence of land use is more significant, whereas geologic and climatic factors become more dominant in large catchments (Pattanayak, 2004).

Although data intensive, process-based mathematical models are capable of reproducing the surface and groundwater processes holistically and accurately in river basins, the lack of the necessary groundwater information often hinders their application in the tropics (Chaves, 1996).

In recent years, economic valuation of environmental services and their extended benefits are becoming more and more effective for addressing water quality and quantity issues in river basins (Classen et al., 2001, Chaves et al., 2004). Pattanayak (2004) has shown that reforestation programs in small Indonesian catchments would increase the percentage of base flow discharge up to 24%, generating an equivalent amount of savings in water collection costs in small communities. This economic incentive can be a powerful motivator to resolve water management issues.

#### 4.1.1 Purpose and scope

The purpose and scope of the present work was the analysis of the hydrological and economic impacts of land use change in a small basin in Brazil, particularly regarding base flow discharge responses. The study follows the UNESCO/GRAPHIC philosophy, namely the assessment of groundwater resources under the pressures of humanity and climate changes. In addition to the hydrologic response, economic valuation is important because its results are more easily comprehended by water users and decision-makers.

Additionally, economic assessments of hydrologic services allow for the establishment of incentive payment programs, which help the mitigation of existing hydrologic problems, as well as the adaptation to future impacts.

#### 4.1.2 Description of the area: the Pipiripau river basin

The area studied under this research was the Pipiripau river basin, situated in the north-eastern corner of the Federal District, in central Brazil (Figure 4.1).

The Pipiripau river basin has an area of 235 km<sup>2</sup>, with central coordinates 15°27'14"S and 47°27'47"W. The river basin has a mean altitude of 950m, gentle topography (average slope of 5.5%), and deep, well drained soils (red oxisols and ultisols), underlain by quartzites, phyllites, and rhythmites, the latter presenting medium to low permeabilities and transmissivities (Chaves and Piau, 2008).

Presently, the main land uses in the catchment are agriculture, pastureland, and natural savannah. Figure 4.2 shows the main land uses in the basin at the present.

Mean annual precipitation in the basin is 1,300mm, with wet summers and dry winters. Mean annual temperature is 22°C. Long-term mean annual stream flow, measured at the basin outlet, is 2.9m<sup>3</sup>/s, and base flow discharge represents 85% of the yearly mean stream flow (Chaves and Piau, 2008).

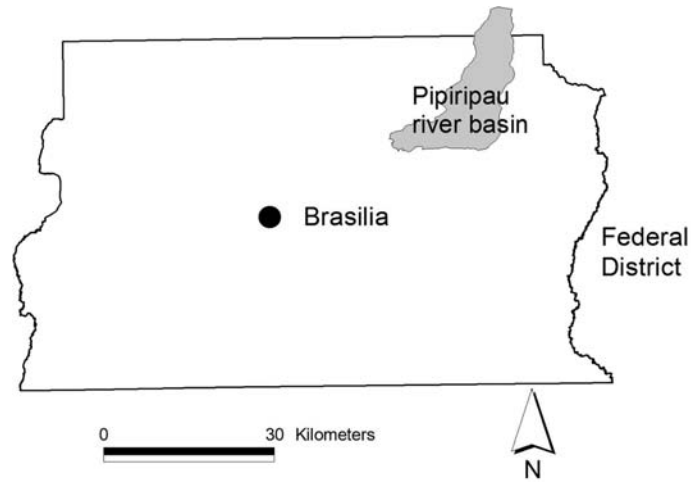


Figure 4.1. Location of the Pipiripau river basin, with respect to the Federal District area (Brazil).

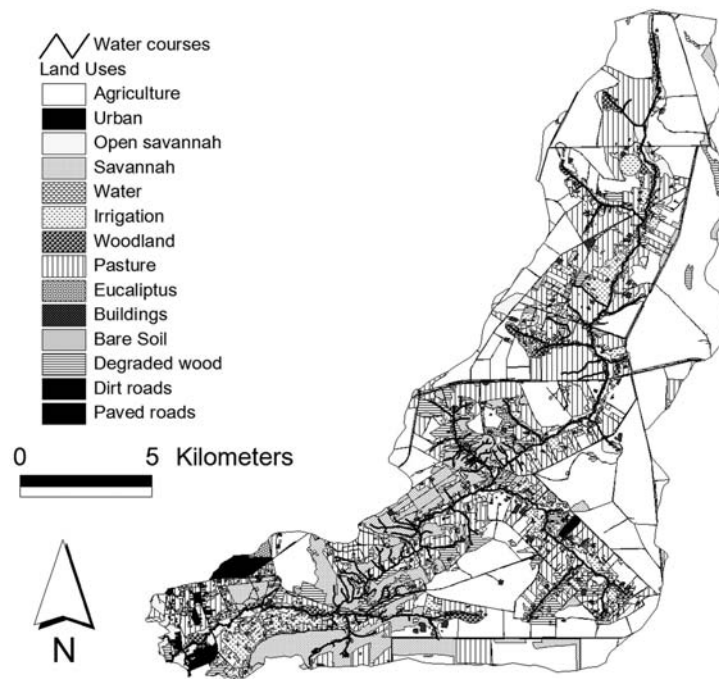


Figure 4.2. Present land uses in the Pipiripau river basin. Source: Chaves and Piau (2008).

#### 4.1.3 Relevance for GRAPHIC

In the last 20 years, the main water uses in the Pipiripau river basin (urban water supply and irrigation) have been competing for the seasonally available river water in the basin, particularly during the long dry winters. However, both users have to observe

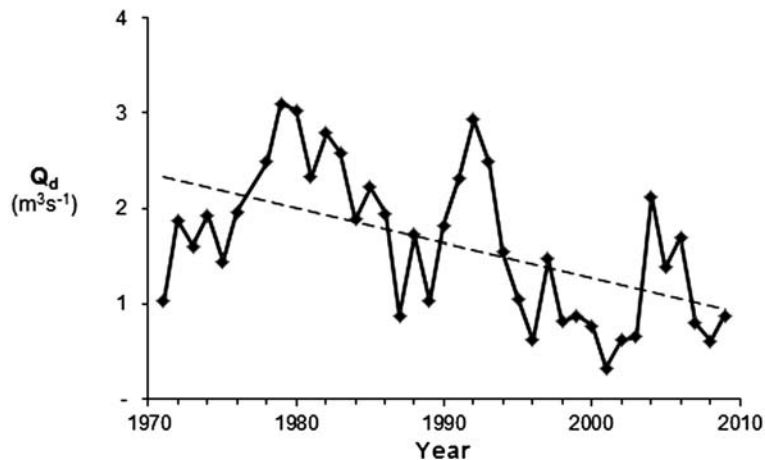


Figure 4.3. Time series of the mean yearly dry season stream flow in the Pipiripau river.

their defined water allocation limits, in addition to the regulated minimum in-stream (environmental) flows, established by federal and state water agencies.

Since the Pipiripau river is not regulated by dams, the reduced water supply during the winter months often leads to water shortages, hindering the development of new businesses and other water-dependent activities.

Additionally, the decline in dry season stream flow indicates a reduction in groundwater discharge in the last 40 years, leading to further water-use conflicts in the basin. Figure 4.3 presents the mean dry-season stream flow values (mean stream flow in the driest 6 months) in the basin.

The dashed line in the time series of Figure 3 shows a significant (95% probability) decreasing linear trend in the dry season discharge in the Pipiripau river. Possible explanations for that behaviour are i) the decreasing trend of annual precipitation in the period, ii) reduced groundwater recharge in the basin as a consequence of increasing land development, iii) increasing water abstractions from the river, or iv) a combination of the three. Since groundwater pumping in the basin is insignificant, it was not considered a possible cause to the reduction of dry season stream flow.

The first process has to do with climate variability/change, and the latter two with human pressures in the basin, in the recent past. These are the key issues addressed by the UNESCO/GRAPHIC project. It is likely that the climate and human pressures are nested, making it difficult to pinpoint the leading cause for the base flow reduction, and therefore increasing the difficulty of establishing appropriate mitigation and adaptation policies (Tucci, 2002).

Since the objectives of the present work were to investigate the possible relationships between the decreasing groundwater discharge trends and the basin land use intensity, to establish a relationship between base flow discharge and basin hydrologic parameters, and to devise an empirical method to estimate hydrological services resulting from land conservation practices in the basin, it is expected that the results could contribute to the GRAPHIC subjects, methods, and experiences.

Additionally, the methodology utilized in the present case study sheds some light on the relationship between climatic variability and groundwater discharge, particularly in data-scarce tropical basins.

## 4.2 METHODOLOGY

In order to achieve the objectives of the study, the methodology was divided in four steps: i) correlation of the annual base flow discharge with the basin land use intensity over the last 23 years; ii) determination of basin curve-number<sup>1</sup> and base flow discharge from existing precipitation and stream flow records; iii) establishment of an empirical relationship between the base flow index<sup>2</sup> basin curve-number and climate variability; and iv) estimation of the hydrological services and economic benefits resulting from three land conservation scenarios in the basin.

### 4.2.1 Correlating annual base flow discharge with basin land use intensity

In this step, basin land use dynamics in the last three decades was obtained from temporal analysis of land-use maps, generated from Landsat satellite images (1984–2006). Land-use designations for these maps were derived using a multi-band, maximum likelihood supervised classification routine (Mather, 1999).

The proportions and frequencies of the land use classes in the basin were obtained for five periods: 1984, 1994, 1998, 2001, and 2006. Additionally, a land use intensity index was applied to the classes and frequencies of the resulting land use maps. The land-use intensity index used was (Ometo et al., 2000; Chaves and Santos, 2009):

$$LUI = \sum_{i=1}^5 f_i w_i \quad (4.1)$$

where: LUI = land use intensity index,  $f_i$  = proportion of the land class  $i$  in the land-use map, and  $w_i$  = weight of the land-use class  $i$ . The weights in equation (4.1) increase as the land use intensity increases, i.e.,  $w = 1$  for natural conditions,  $w = 2$  for little disturbances in the natural condition,  $w = 3$  for agriculture and pasture,  $w = 4$  for low density urban areas, and  $w = 5$  for dense urban areas (Chaves and Santos, 2009). The weights in equation (4.1) correlate well with NRCS (1972) curve-number, where impermeable urban areas has twice or more the runoff potential and recharge abatement of pervious natural areas.

In order to avoid climate interference in the analysis, mean annual stream flow of the driest 6 months ( $Q_d$ ) of the Pipiripau river was normalized by annual basin precipitation. The normalized variable  $Q_d/P$  was then plotted against the corresponding LUI for the five years studied, and an empirical relationship was obtained.

### 4.2.2 Obtaining basin curve-number and base flow discharge from stream flow data

The next step was the estimation of the basin curve-number (CN2) from the daily rainfall and stream flow records for the 1991–2009 period. In order to separate storm runoff

<sup>1</sup>Runoff coefficient, developed by the NRCS (1972).

<sup>2</sup>Ratio of base flow to total stream flow.

from base flow, the daily stream flow data was passed through a digital filter, originally developed by Nathan and MacMahon (1990):

$$q_t = \alpha q_{t-1} + \frac{1 + \alpha}{2} (Q_t - Q_{t-1}) \quad (4.2)$$

where:  $q_t$  ( $\text{m}^3 \text{s}^{-1}$ ) = filtered stream flow;  $Q_t$  ( $\text{m}^3 \text{s}^{-1}$ ) = original stream flow at day  $t$ ; and  $\alpha$  = filter parameter, taken as 0.925 (Nathan and MacMahon, 1990). Daily base flow discharge ( $Q_b$ ) is simply the difference between  $Q_t$  and  $q_t$  in equation (4.2).

After the hydrograph separation, significant storm flow hydrographs, resulting from precipitation events with a volume over 10 mm in three consecutive days, were integrated, and a direct runoff volume ( $Q_r$ , in mm) was obtained. A corresponding CN2 value for each storm hydrograph was obtained through the iterative solution of the following equation (NRCS, 1972):

$$Q_r = \frac{\left[ P - 0.2 \left( \frac{25400}{\text{CN2}} - 254 \right) \right]^2}{\left[ P + 0.8 \left( \frac{25400}{\text{CN2}} - 254 \right) \right]} \quad (4.3)$$

where:  $Q_r$  (mm) = runoff volume of the storm flow hydrograph,  $P$  (mm) = precipitation volume of the event, CN2 = curve number for medium antecedent moisture conditions. Appropriate corrections were made in the calculated CN2 whenever drier ( $P_a < 3.56$  mm in the previous 5 days) or wetter ( $P_a > 5.33$  mm) antecedent soil moisture conditions (AMC) occurred (Chow et al., 1988).

Annual means of calibrated and corrected CN2 values were obtained for each hydrologic year in the stream flow series, and a global mean of CN2 obtained for the basin. To verify the accuracy of the calibrated CN2 value, it was compared with the weighted average CN2 value obtained from the NRCS (1972) table (below), calculated by the GIS and using the basin soils and land-use map.

#### 4.2.3 Empirical relationship between the base flow index and the normalized runoff coefficient

In this step, the dimensionless yearly mean base flow index ( $Q_b/Q$ ) in the period 1992–2009 was plotted against the normalized yearly curve number ( $\text{CN2}/P$ ). Outliers with too high or too low base flow indices were removed from the analysis. The obtained empirical relationship was later used in the estimation of the hydrologic services resulting from different land conservation scenarios, by corresponding changes in the basin CN2 coefficient.

#### 4.2.4 Estimating and valuing hydrological services resulting from land conservation scenarios

Since reforestation and best management practices (BMPs) can increase base flow discharge (Klöcking and Haberlandt, 2002; Schilling and Libra, 2003), the mean annual base flow increment in the Pipiripau river basin was estimated under three hypothetical land use scenarios, starting from the present (baseline) land use conditions.

Target areas for land conservation were defined based on environmental liabilities previously identified in the basin, including forest cover deficits in riparian strips and property reserves (reforestation), and unprotected aquifer recharge zones (BMPs).

Table 4.1 below lists the three land conservation scenarios analyzed in the study. These scenarios considered three possible climate conditions: average (A, mean annual precipitation), dry (D, mean annual P minus one standard deviation), and wet (W, mean annual P plus one standard deviation) years.

According to Table 4.1, a total of nine combinations of land use/climate scenarios were analyzed. In order to estimate the mean annual base flow discharge increment resulting from the each of the nine scenarios above, and starting from the calibrated CN2 value for the basin (baseline), new weighted CN2 values were obtained for the basin with the aid of the GIS and Table 4.2 below.

The new basin curve-number (CN2') under the different land conservation scenarios was the weighted mean of CN2 values of Table 4.2 and the new soils and land use/management frequencies:

$$CN2' = \frac{\sum_{i=1}^{11} CN2_i A_i}{A} \tag{4.4}$$

Table 4.1 Land conservation scenarios and climate conditions used in the estimation of the hydrologic services in the Pipiripau river basin.

Scenario Number	Type of land conservation practice	% of Basin Area	Climate condition
1	Reforestation of riparian and legal reserve areas with native tree species	9.5%	D/A/W
2	BMPs in agricultural and pastureland in recharge areas (no-till agriculture, terraces)	44.1%	D/A/W
3	Both scenarios (1+2)	53.6%	D/A/W

Table 4.2 CN values for a combination of soil type and land use. Source: NRCS (1972).

Land Use	Land Management	Hydrologic Soil Group			
		A	B	C	D
Agriculture	Without conservation practices	72	81	88	91
	With conservation practices	62	71	78	81
Pastureland	Poor condition	68	79	86	89
	Good condition	39	61	74	80
Savannah	Good condition	30	58	71	78
Woodland	Regular cover	45	66	77	83
	Good cover	25	55	70	77

where:  $CN2'$  = the new basin curve-number incorporating the land conservation scenario,  $CN2_i$  = curve-number of the soil and land-use/management  $i$ ,  $A_i$  = area corresponding to the soil and land-use combination  $i$ , and  $A$  (ha) = total basin area.

The base flow discharge under different land-use and climate scenarios was computed with an empirical linear regression, obtained from the observed data, with the form:

$$Q_b/Q = a(CN2/P) + b \quad (4.5)$$

where:  $a$  = the angular coefficient of regression,  $b$  = the linear coefficient,  $Q$  and  $Q_b$  are the stream flow and base flow discharge ( $m^3/s$ ), respectively,  $CN2$  is the basin curve-number, and  $P$  (mm) is the annual precipitation.

After  $Q_b$  was calculated in the baseline (land use and climate) condition, a new base flow discharge ( $Q_{b1}$ ) was computed by equation (4.5) for the desired land use and climate combination.  $P$  and  $Q$  values in equation (4.5) were set at three levels each (dry, average, and wet conditions). The increment in annual base flow discharge for a given soil and land conservation/climate scenario was therefore:

$$\Delta Q_b = Q_{b1} - Q_{b0} \quad (4.6)$$

where:  $\Delta Q_b$  ( $m^3/s$ ) = mean annual increment in base flow discharge in the basin,  $Q_{b1}$  ( $m^3/s$ ) = mean annual flow discharge under the new land conservation/climate scenario, and  $Q_{b0}$  ( $m^3/s$ ) = mean annual flow discharge under the baseline scenario.

Once the base flow discharge increments were obtained for each soil and land conservation/climate combination, the resulting economic externality was estimated by the product of the annual volume of base flow increment and the average household water price in the basin, taken as US\$ 1.5 per  $m^3$  (CAESB, 2011).

## 4.3 RESULTS AND DISCUSSION

### 4.3.1 Correlation between the dry season discharge and basin land use intensity

Figure 4.4 presents the land use dynamics in the basin between 1984 and 2006. According to that Figure, savannah, woodland and grassland have been replaced with agriculture and other anthropic uses in a steady fashion during the period.

Figure 4.5 below shows the correlation between land use intensity index (LUI) and the normalized dry season discharge ( $Q_d/P$ ) in the Pípiripau river basin, during the period 1984–2006.

LUI almost doubled in the period studied, from 1.88 in 1984 to 3.43 in 2006, with a corresponding decrease in  $Q_d/P$ . A good fit ( $R^2 = 0.92$ ) was obtained for the linear regression, with the advantage that climate interference was eliminated.

Mixed results regarding land use conversion and base flow discharge were found in the literature. While Krause (2002) reported a significant decrease of the base flow index ( $Q_b/Q$ ) as a result of conversion of forests to agriculture in a German basin, Siriwardena

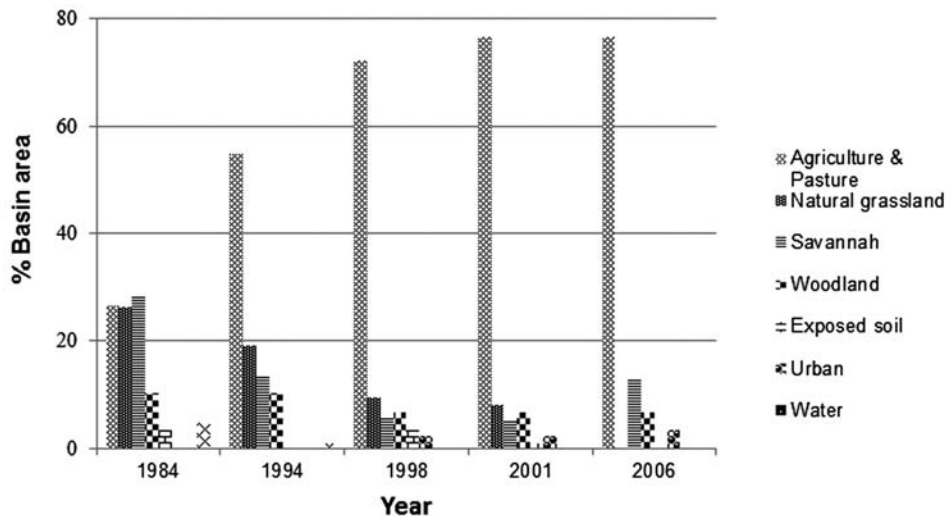


Figure 4.4. Land use dynamics in the Pipiripau river basin in the period 1984–2006.

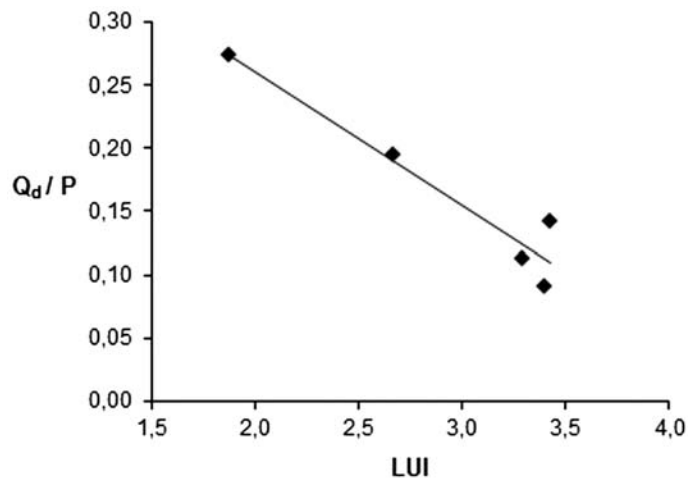


Figure 4.5. Relationship between the normalized dry-season stream flow and the land use intensity index in the Pipiripau river basin between 1984 and 2006.

et al., (2006) found the opposite in a basin in Queensland (Australia). Considering that other factors (rainfall variability, evapotranspiration) play a role in base flow discharge generation, it is reasonable to assume that results would be basin specific (Brooks et al., 2003).

Table 4.3 Yearly precipitation (P), mean stream flow (Q), mean base flow discharge ( $Q_b$ ), base flow index ( $Q_b/Q$ ), calibrated CN2, and normalized CN2 (CN2/P) for the Pípiripau river basin, in the period 1992–2009.

Year	P (mm)	Q (m <sup>3</sup> /s)	$Q_b$ (m <sup>3</sup> /s)	$Q_b/Q$	CN2	CN2/P
1992	1,417	4.0	3.5	0.877	73.4	0.052
1993	1,383	4.6	4.1	0.887	73.4	0.053
1994	1,254	3.2	2.7	0.857	79.2	0.063
1995	1,431	2.1	1.9	0.908	66.4	0.046
1996	951	1.4	1.2	0.855	69.6	0.073
1997	1,479	2.0	1.6	0.807	73.3	0.050
1998	1,085	2.0	1.7	0.841	81.6	0.075
1999	1,340	1.8	1.5	0.840	72.0	0.054
2000	1,063	2.0	1.6	0.823	73.9	0.069
2001	912	1.2	1.0	0.809	74.1	0.081
2002	1,123	1.7	1.3	0.784	73.0	0.065
2003	1,213	1.6	1.3	0.851	68.2	0.056
2004	1,627	3.4	2.7	0.795	75.3	0.046
2005	1,316	2.7	2.3	0.862	70.4	0.054
2006	1,428	3.0	2.6	0.868	69.8	0.049
2007	1,228	2.5	2.1	0.859	69.0	0.056
2008	1,158	1.5	1.4	0.883	68.1	0.059
2009	1,147	1.7	1.5	0.882	68.2	0.059
<b>Means</b>	1,253	2.4	2.0	0.849	72.2	0.059

#### 4.3.2 Base flow discharge hydrographs and basin curve-number (baseline condition)

Table 4.3 below presents the yearly precipitation, stream flow (Q), base flow discharge ( $Q_b$ ), base flow index ( $Q_b/Q$ ), and the calibrated CN2 values for the Pípiripau river basin, in the 1992–2009 period (baseline condition).

The mean calibrated CN2 for the catchment in the baseline condition, reflecting a combination of basin soils and land use characteristics, was 72.2, very close to the estimated (table) weighted average (CN2 = 70.7), indicating that the calibration and the hydrograph separation process were adequate.

Although Table 4.3 indicates that CN2 tended to decrease in the studied period, since it is strongly correlated with annual precipitation, the ratio CN2/P was a better indicator of basin condition.

Mean yearly precipitation in the period was 1,253 mm, with a standard deviation of 191 mm. Mean base flow was 2.0 m<sup>3</sup>/s, and mean base flow index was 0.85. Figure 4.6 presents the correlation obtained between the base flow index and the normalized curve-number in the Pípiripau river basin.

Figure 4.6 shows that a relatively good fit was obtained for the linear regression between  $Q_b/Q$  and CN2/P. The dispersion in the data reflects the changes in watershed/aquifer conditions in the period studied.

Figure 4.6 also indicates that, for a given climate condition, an increase in CN2 would decrease the base flow index, i.e., the relative contribution of base flow discharge to total stream flow. The advantage of using the empirical function of Figure 4.6 is

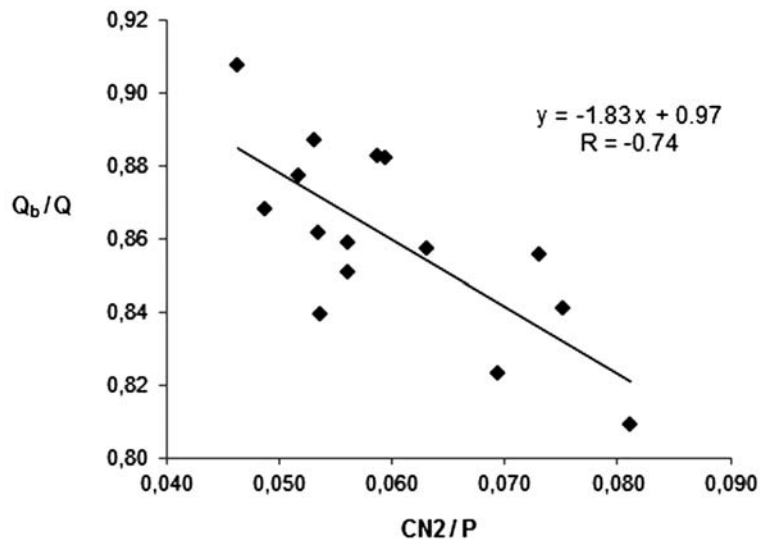


Figure 4.6. Correlation between the base flow index and the normalized curve-number for the Pipiripau river basin during studied period.

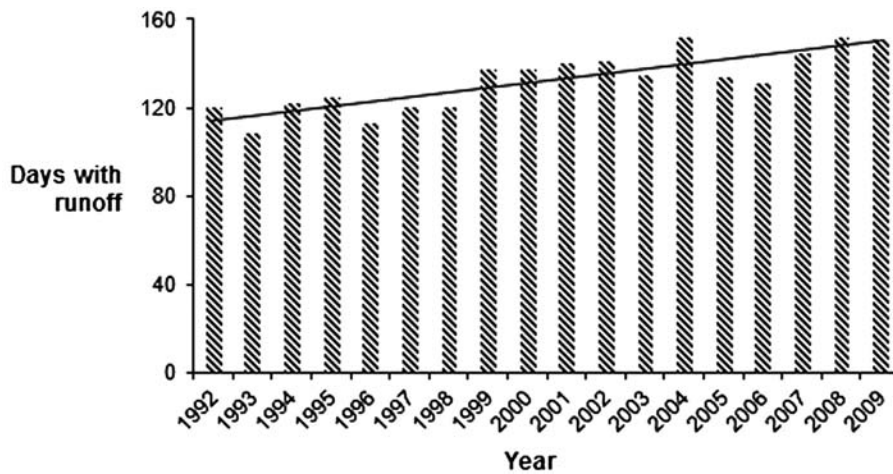


Figure 4.7. Number of days of the year with storm runoff in the Pipiripau river basin.

that the normalizations in  $Q_b$  and in  $CN2$  eliminate intrinsic climatic variability, allowing for the isolation of the land use effects on base flow discharge.

Although there is a resemblance between Figures 4.5 and 4.6, the independent variable in the latter ( $CN2/P$ ) has more hydrologic meaning, and therefore it is more useful for predictions of future basin behaviour.

Figure 4.7 below explains part of the behaviour of decreasing base flow index with increasing  $CN2/P$ , as seen from Figure 4.6. The former shows that the number of days with direct runoff in the Pipiripau basin has increased linearly in the period studied, contributing to the reduction of groundwater recharge and base flow discharge.

## 4.3.3 Hydrological services resulting from land conservation scenarios

The weighted averages of CN2 for the Pipiripau river basin under the baseline condition and land conservation scenarios are presented in Table 4.4.

According to Table 4.4, there would be a significant reduction in the basin CN2 after the introduction of the three land conservation scenarios, the highest decrease being under scenario 3, involving reforestation and the implementation of conservation practices in the agricultural areas.

Figure 4.8 shows the hydrological service with respect to base flow discharge ( $\Delta Q_b$ ) and the additional revenue for the water utility company ( $\Delta R$ ), as a function of the three land conservation scenarios, under the three climate conditions analyzed.

According to Figure 4.8, there would be a substantial increase in the dry season water availability in the basin, from 94,300 m<sup>3</sup> (0.4% of mean dry season flow) in a dry year under scenario 1, to 754,800 m<sup>3</sup> (3.0% of mean dry season flow) in a wet year under scenario 3. The additional revenues would range from US\$ 123,900 per year to US\$ 1,032,400 per year, respectively. The benefit/cost ratios for would be 0.08 and 2.93 for scenarios 1 and 3, respectively, indicating that the scenarios involving land conservation practices were more effective economically.

An increase of 25% in the base flow index of nine American basins was reported by Schilling and Libra (2003), as a result of improved conservation practices during the last 40 years, relative to previous conditions. Pattanayak (2004) reported that reforestation programs would increase the percentage of base flow discharge up to 24%, generating an equivalent amount of savings in water collection costs in small Indonesian communities.

Although land conservation practices such as reforestation can potentially increase basin evapotranspiration (ET) and decrease base flow discharge, the small proportion of

Table 4.4 Calibrated (baseline) and prospective (scenarios) CN2 values for the Pipiripau river basin.

Scenario	Baseline	Scenario 1	Scenario 2	Scenario 3
CN2	72.2	69.2	64.8	59.7

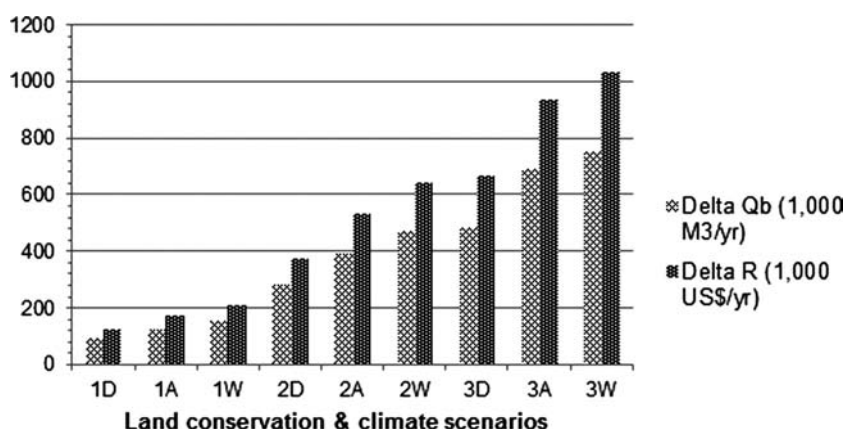


Figure 4.8. Hydrological services and additional revenues resulting from the land conservation scenarios in the Pipiripau river basin, with respect to the baseline condition.

reforestation (<10% of the basin area) of scenarios 1 and 3 would not affect ET in a significant manner. In the case of scenario 2, the mulch cover of no-till agriculture would in fact reduce ET, with respect to the baseline condition.

#### 4.4 POLICY RECOMMENDATIONS

The additional revenues generated by the increased base flow discharge (Figure 4.8) could be used to pay for the hydrologic services provided by participating farmers, creating a virtuous circle of land conservation and flow stabilization in the basin.

The hydrologic services and revenues would also demonstrate to the decision makers and water managers the economic feasibility of land conservation, which could lead to the design and implementation of land conservation projects in the future. In addition to the mitigation of the land use intensification in the basin, land conservation scenarios would also provide an adaptation strategy against future climate change.

Although there are supporting examples of the positive effect of land conservation on base flow discharge in the literature, the results of the present case-study reflect a specific situation, and discretion shall be used in transferring them to other river basins. However, the simplicity and robustness of the presented methodology facilitate its application to other data-scarce watersheds, where data intensive, process-based models could not be used.

#### 4.5 FUTURE WORK

Considering that the Pipiripau river basin has been an object of hydrologic research in the last ten years, future activities in the Pipiripau river basin will involve:

- The survey and mapping of groundwater levels in the basin;
- The downscaling of GCM outputs to the basin scale and estimation of future climate change impacts in basin hydrology;
- The application of process-based models, such as SWAT;
- Continuous monitoring of stream flow and base flow in the basin, during and after the implementation of land conservation programs;
- The analysis of the vulnerability and risk of groundwater contamination by pesticides;
- Hydrologic and economic effectiveness of the implementation of agri-environmental (incentive payment) programs in the basin;
- The comparison of the results with other GRAPHIC case studies around the world.

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