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A tool for community-based assessment of the implications of development on water security in hillside watersheds

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Abstract

Development and population growth in Latin American countries with steep slope farming are likely to further increase pressures on water and land resources. A methodology was developed for assessing water availability and use under different development pathways at a watershed scale to determine whether water security is a potential problem, and if so, under what conditions it is likely to occur. This methodology makes use of a GIS-based spatial water budget model for simulating stream water availability, water use and stream flow control on a daily basis at a watershed scale. Here, we analysed water availability under three plausible development scenarios for the 3246 ha Cabuyal River watershed in southwest Colombia in the year 2025: Corporate Farming (CF), Ecological Watershed (EW), and Business as Usual (BU). Simulated average river flows at the watershed outlet were, respectively, 874, 796 and 925 l s^{-1} for the CF, EW and BU scenarios. The contribution of base flow to river flow (base flow index) was on average, 80.8, 85.6 and 77.9%, respectively, for the three scenarios. The watershed had the potential to meet the anticipated increase in water use under each explorative scenario. However, dams were necessary to store irrigation water in the CF scenario, otherwise over 60% of the available water would have been used during the dry season. Such a high figure raises concerns about effects on aquatic and riparian ecology, concentrations of potential contaminants, water reserves for especially low rainfall years, and the watershed resilience to meet temporarily higher water needs during the day. Analyses indicated that current water-use conflicts in the watershed can be resolved if irrigation water supply is separated from drinking water supply. This study helped reduce some of the

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complexity associated with the interdependencies between land and water resources, the impact of using them, and spatial linkages within the watershed. Results of this study can be used for teaching local stakeholders about basic landscape responses and helping multi-institutional alliances to become proactive and to guide development to the benefit of local communities.

Keywords: Water security; Water use; Land cover; SWBM; Explorative scenario; Cabuyal River watershed; Colombia; Simulation model

1. Introduction

Water availability and quality have become major threats to food security, human health and natural ecosystems. An estimated 1.4 billion people, amounting to a quarter of the world population, or a third of the population in developing countries, live in regions that will experience severe water scarcity by 2025 (Seckler et al., 1999). People in developing countries are particularly at risk in areas experiencing high population growth and limited means of managing water resources. One example is areas in Latin American countries with steep slope hillsides where small-scale farming is the predominant production activity and means of food supply. Table 1 gives basic statistics on population size and available annual fresh water resources (AWR) for a number of such countries.

Several studies have been conducted to quantify fresh water availability on a national level and countries were ranked according to the per capita available 'annual water resources' (AWR). Raskin et al. (1997) considered water scarce when more than 40% of the AWR was withdrawn. Falkenmark et al. (1989) considered fresh water shortages local and rare for AWR values above 1700 m^3 per capita, whereas water availability was considered a primary constraint to life for AWR values less than 500 m^3 per capita. Seckler et al. (1998) also used an AWR approach,

Table 1
Basic statistics on population and water availability in selected Latin American countries with a high percentage of the area under steep-slope agriculture

Country	Steep area[a] (%)	Population[b] (million)	AWR[c] (km^3)	Per capita AWR (m^3)
Bolivia	40	8.33	300	36 019
Colombia	40	38.91	1070	27 503
Costa Rica	70	3.80	95	25 013
El Salvador	75	6.32	19	3007
Ecuador	65	12.65	314	24 830
Guatemala	75	12.22	116	9491
Honduras	80	6.49	63	9776
Nicaragua	80	4.69	175	37 282
Peru	50	25.66	40	1559
Venezuela	70	24.17	1317	54 489

[a] Percent of the area under agriculture with slopes > 30% (source: CIAT, 1996).
[b] Estimated 2000 population according to United Nations (1998) medium growth projection.
[c] AWR: annual (fresh) water resources (source: Seckler et al., 1998).

but applied it to both low and high irrigation efficiency scenarios for 2025. With the exception of Peru, the sample of Latin American countries in Table 1 considerably exceeds the threshold of 1700 m^3 AWR per capita, suggesting an abundance of available fresh water and enough leeway to expand water use in the future.

However, water availability is distributed in a spatially and temporally heterogeneous manner in patterns that may differ from water needs. The data in Table 1 do not provide insight on local water security at spatial scales smaller than a country, for example, a small watershed. Watersheds have been widely recognized as appropriate biophysical or socioeconomic units for water resources management (Brooks et al., 1997; Rhoades, 1998; Lal, 1999). Major development organizations, ranging from the World Bank to small local non-governmental organizations are promoting watershed management in many communities throughout the world (Rhoades, 1998). The watershed has also been adopted for organizing research and development activities at research centers such as the International Center for Tropical Agriculture (Knapp et al., 1999) and the International Water Management Institute (McKinney et al., 1999).

Despite the currently large AWR of Colombia (27507 m^3 $year^{-1}$ per capita), early warning signs of water use conflicts have been observed in the 3246-ha Cabuyal River watershed in southwest Colombia (CIAT, 1993; Ravnborg and Ashby, 1996). Local stakeholders identified reduced or insufficient water availability during the dry season as a particularly serious problem. The streams in this watershed are the primary source of water to serve domestic, industrial, and agricultural water needs. Water extraction from streams has always been virtually unregulated (De Fraiture et al., 1997), potentially allowing farmers to use large volumes for irrigation. Such practices could reduce downstream water availability to levels below water needs. This may constitute an immediate health risk to the population, and crop losses may occur without sufficient irrigation. Local stakeholders also argued that land cover change — in particular deforestation — and the lack of adequate soil conservation techniques affected the hydrological behavior of the watershed, resulting in less predictable river flow rates and higher peak flow rates (De Fraiture et al., 1997). Some people are also affected by the fact that some of the natural springs in the watershed dry up and watercourses move down slope in the dry season. Poor families that are not connected to piped drinking water and farmers without good irrigation equipment are most affected by reduced accessibility to water. And lastly, although downstream communities have the advantage of benefiting from a larger catchment area and thus higher stream flow, they may also experience the greatest effects of any changes in the land and water use that occur at higher elevations.

Nearly 10 years of experience with water resources management decision making in the Cabuyal River watershed showed that decisions were sometimes based on an incomplete understanding of (1) the interdependencies between land use and stream water yields, (2) the possible consequences of constructing dams and water extraction on water availability in other communities, and (3) upstream–downstream connections in the watershed. It is increasingly important to provide quantitative information on these relationships, as well as on how water supply and demand could change under different future conditions. This is considered a critical part in

(1) negotiating compromises to resolve conflicts, (2) gaining commitment of local stakeholders to institutional arrangements and resource preserving management practices, and (3) helping decision-makers to guide development to the benefit of local communities (Knapp et al., 1999).

The objective of this paper was to assess the potential changes in availability and use of water under different development pathways in the Cabuyal River watershed, using the Spatial Water Budget Model (SWBM, Luijten et al., 2000b). First, we quantified the effects of different land uses on the hydrological balance by simulating three uniform land uses: a fully forested watershed, only cropland, and only bare soil. Although it is unlikely that any single land use will ever cover the entire watershed, these results helped characterize the hydrological response of the watershed under these extreme situations, and are also useful for teaching local stakeholders about basic principles of the water cycle. Secondly, we assessed water supply and demand under three plausible scenarios for the year 2025 (Corporate Farming, Ecological Watershed and Business as Usual) and discuss the implications for water resources management. We provide a description of SWBM's capability of simulating stream water budgets and flow control structures (i.e. dams), which were particularly important for analysing the scenarios.

2. Materials and methods

2.1. Description of the Cabuyal River watershed

The Cabuyal River watershed is located between 76°36′–76°30′ W and 2°42′–2°52′ N in the Cauca province in southwest Colombia (Fig. 1). The Pan-American Highway links the watershed with Cali, the third largest city of Colombia, one hour away. The area of the watershed is 3246 ha, embedded within 22 administrative units ('veredas') totaling 7525 ha. Approximately 5400 people were living in the administrative Cabuyal region in 1995 (De Fraiture et al., 1997). Elevation in the watershed ranges from 1175 to over 2200 m above mean sea level. Nearly half of the area has slopes greater than 30 degrees with slopes up to 75 degrees (determined from a Digital Elevation Model). The landscape is heterogeneous with many small plots of natural forest, bush scrub, pasture, coffee and various crops. This fragmented landscape is characteristic of many steep hillsides in Latin America. The main production activity is subsistence and cash cropping (maize, beans, coffee, cassava, coffee and irrigated vegetables, mostly tomato) by small-scale farmers. Industrial activity is limited to the processing of cassava in small plants and on some farms. In 1995, approximately 4.7 million kg cassava was processed to produce 0.94 million kg starch (E.B. Knapp, 1998, personal communication).

The watershed is a headwater watershed, i.e. there is no run-on from adjacent areas. Unlike many regions in the USA and Europe, stream water originates from the areas where people live and agricultural and industrial activities take place, and the streams provide the water used by farms, households and industries. Part of the water of the Cabuyal River is diverted into small pipes to provide clean drinking

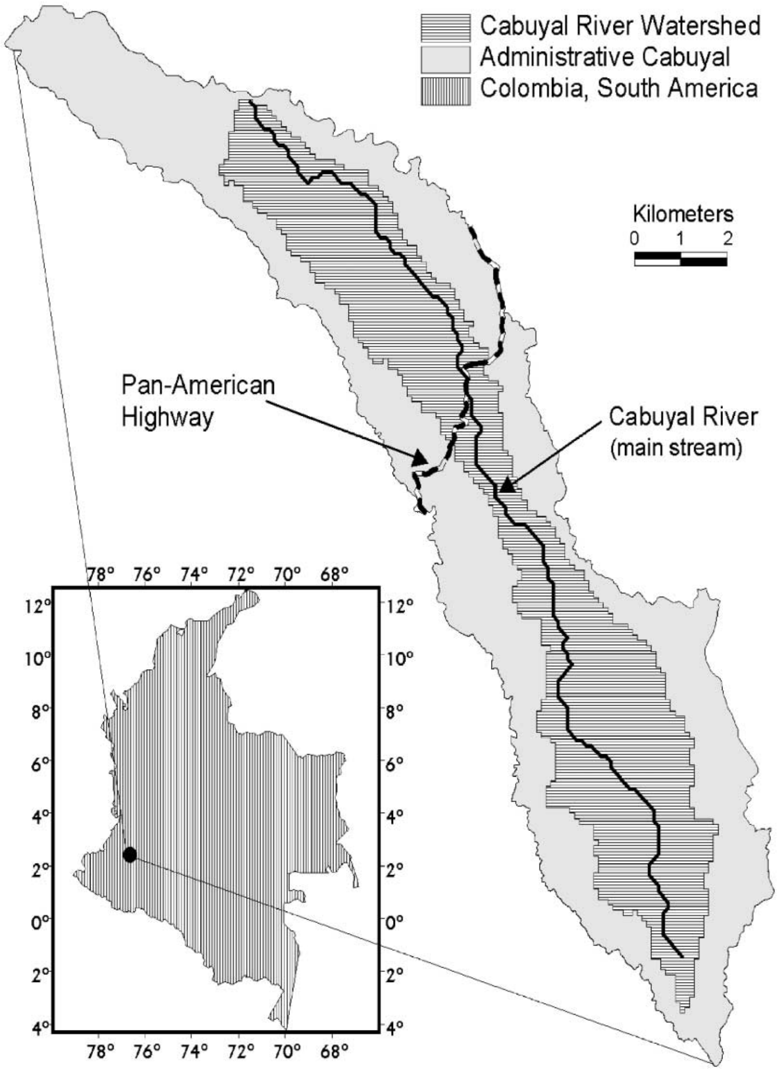

Fig. 1. Geographic location of the Cabuyal River watershed. The rectangular area around the administrative region is 16×20 km.

water to about 85% of the households (De Fraiture et al., 1997). Like most rural areas of Latin America, a significant minority of the poorest families, and those living at the fringes of the watershed, gather water directly from streams.

2.2. SWBM

SWBM is a continuous, distributed parameter, watershed scale model that simulates water supply and demand over space and time on a daily basis using GIS raster structures (Luijten et al., 2000a, 2000b). It was designed for assessing water availability and use under different development pathways to determine whether water security is a potential problem, and if so, where and when it is likely to occur (Luijten, 1999). Processes that are simulated by SWBM are: (1) land unit water balance; (2) water flow to streams; (3) stream water flow balance; (4) water storage behind dams and in small man-made reservoirs; and (5) water extraction from reservoirs and streams for domestic, agricultural and industrial uses. The model was designed specifically for the needs and resources of developing countries in Latin America and the Caribbean, but can be applied in other areas as well. Luijten et al. (2000a) presented the governing equations of the processes (1), (2) and (3) and explained the impact of land cover change on the hydrological balance of the Cabuyal River watershed. Here, we focus on the processes (4) and (5).

A stream is represented by a series of connected grid cells (Luijten, 2000a), each of which receives an accumulated flow beyond some threshold. Stream water is assumed to flow sufficiently fast so that water flowing into the stream at any point in the watershed will reach the watershed outlet within a day, a reasonable assumption for hillside watersheds. Dams may be located anywhere in the river to store water for use at a later time or to regulate flow rates. Each dam is associated with a constant storage capacity. The operation of a dam is characterized by water intake settings, water release settings, and (optionally) minimum required and maximum allowed river flow rates. These settings may vary from day to day. The daily operation and the physical dimensions of a dam required to realize a certain storage capacity are engineering aspects that are assumed technically feasible but are not taken into account by the model (Luijten, 1999).

The change in storage behind a dam at stream cell x ($\Delta\mathrm{ST}_{x,d}$, m^3 day^{-1}), with $0<x<N$ and N being the stream cell at watershed outlet, is calculated as:

$$\Delta\mathrm{ST}_{x,d} = V_{x-1,x,d} + V_{\mathrm{RO},x,d} + V_{\mathrm{LF},x,d} - V_{\mathrm{USE},x,d} - V_{x,x+1,d} \quad (1)$$

where $V_{x-1,x,d}$ is the water volume inflow from the neighboring upstream cell $x{-}1$; $V_{\mathrm{RO},x,d}$ and $V_{\mathrm{LF},x,d}$ are the accumulated rates of, respectively, surface run-off and lateral flow into stream cell x from adjacent land units; $V_{\mathrm{USE},x,d}$ is the daily volume of water extracted from stream cell x to meet water demands, and $V_{x,x+1,d}$ is the daily volume of water released to flow downstream. All terms have unit m^3 day^{-1}. Luijten et al. (2000a) presented the governing equations of surface run-off and lateral flow toward streams. Eq. (1) also applies to stream cells that do not have a dam ($\Delta\mathrm{ST}_{x,d}=0$ at all time).

Typically, water is extracted at a limited number of locations, such as where aqueducts intake water, industries are located, or fields are irrigated. These locations are georeferenced and can be selected from a map that is displayed on the screen. SWBM allows water use from any reservoir or stream cell x at any day d for domestic use ($V_{\mathrm{DOM},x,d,}$), industrial use ($V_{\mathrm{IND},x,d}$) and/or agricultural use ($V_{\mathrm{AGR},x,d}$), all in m^3 day^{-1}. The rate of water extraction at every location can be specified per day d (different rates each day) or for a period $d_1 \ldots d_2$ (identical rate for all days within that period). Total water use from stream cell x is calculated daily as:

$$V_{\mathrm{USE},x,d} = V_{\mathrm{DOM},x,d} + V_{\mathrm{IND},x,d} + V_{\mathrm{AGR},x,d} \tag{2}$$

If the supply of water is insufficient to meet water demand (after accounting for minimum stream flow requirements, if any), priority is first given to meeting domestic, then industrial and lastly agricultural water demand. This reflects current water allocation practices in the Cabuyal River watershed (De Fraiture et al., 1997), however, other priorities could be specified. Eqs. (1) and (2) are evaluated in downstream direction, i.e. starting with the stream cells at the highest point of all primary stream branches (i.e. those that do not have tributaries) and ending with stream cell $x = N$ at the watershed outlet. Changes in river flow are then properly accumulated throughout the stream network.

2.3. Scenarios analysed

Two different types of scenarios were developed and analysed. They were compared with the actual land and water use situation in the 1990s (base scenario). First, three uniform land uses were analysed: a fully forested watershed, only cropland, and only bare soil. Forest has a dense canopy with mulch and litter on the soil surface that can intercept much rain and prevent surface run-off. Bare soil, on the other hand, is highly susceptible to surface run-off and erosion. Cropped land is assumed to be a mixture of different crops in different stages of development, with some fallow plots occurring during part of the year. Although it is unlikely that any single land use will ever cover the entire watershed, this analysis was useful for characterizing potential water yields from the watershed under these extreme land uses.

Secondly, three explorative scenarios were developed to describe contrasting but plausible directions of development for the Cabuyal River watershed in the year 2025 (Luijten, 1999). The *Corporate Farming* (CF) scenario describes an agribusiness future dominated by large corporate farms. High-tech production of irrigated vegetables and sugarcane, intensive cattle ranching and processing of agricultural products are the dominating activities. Land and water resources are intensively used; 300 ha cropland and 300 ha pasture (out of 3246 ha) is irrigated from June through October. Irrigation management was assumed to have an efficiency of 75%, resulting in a conservative estimate of demand. Six dams with a storage capacity of 300 000 m^3 each are located along the river (Fig. 2b). As there is currently no dam in the Cabuyal River watershed, the locations and storage capacities of the six dams were chosen hypothetically albeit well thought-out to meet the following criteria: (1) a fairly evenly distribution that minimizes the average distance to reach them; (2) strategic locations that make each dam equally useful for controlling river flow rates and water storage; and (3) storage capacities that are sufficient to demonstrate that the dams can meet their objectives. Population growth was assumed slightly below the United Nations (1998) low projection for Colombia (Table 2).

In the Ecological Watershed (EW) scenario, regional authorities and local communities have a strong mandate to conserve forest, land and water resources, and regulate stream flows. A large area has been reforested. Fifteen smaller dams with a storage capacity of 100 000 m^3 each are used to control flow rates throughout the

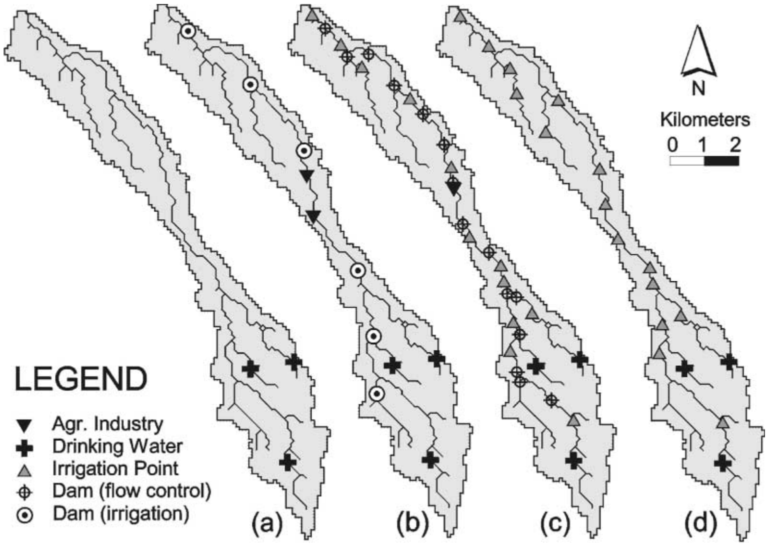

Fig. 2. Locations where water is extracted from streams in the Cabuyal River watershed for domestic, industrial and agriculture use and where flow control structures are present. (a) Actual situation in 1989; (b) Corporate Farming scenario; (c) Ecological Watershed scenario; (d) Business as Usual scenario.

Table 2
Demographic data for the 7526 ha administrative Cabuyal region, for 1995 and estimates for three scenarios in 2025[a]

Scenario	Persons	Families	Growth rate 1995–2025
Actual, 1995	5357	910	N/A
Corporate farming	6900	1250	29%; below the low UN projection
Ecological watershed	7870	1340	47.1%; medium UN projection
Business as usual	8545	1450	59.5%, high UN projection

[a] The 1995 data are based on a census by CIAT. The growth rates are based on United Nations (1998) population projections for Colombia.

watershed. A minimum required flow rate of 350 l s^{-1} and a maximum allowed flow rate of 1500 l s^{-1} at the watershed outlet were sustained by 15 smaller flow control structures throughout the watershed (Fig. 2c). Irrigation was applied to 200 ha cropland from June through October, taken at equal rates from 12 locations in the river. The United Nations medium population growth scenario was assumed (Table 2).

Under the Business as Usual (BU) scenario, small-scale subsistence farming and some processing of cassava are the dominant activities in the watershed, as in the 1990s. However, much forest has disappeared due to slash and burn activities, and an increasing area of land has eroded or is bare soil, reflecting the lack of incentives for soil and land conservation. There are no dams. Water for irrigation was taken at

15 locations (Fig. 2d) and applied to 145 ha of vegetable plots near houses from June through October. A lower irrigation efficiency of 50% was assumed, consequently more irrigation water was used per hectare. Population growth was assumed equal to the United Nations high projection (Table 2).

2.4. Data

The direction of flow and the location of streams were derived from a digital elevation model (DEM) at 100 m resolution, which was the maximum resolution to adequately represent the steep topography of this particular watershed (Luijten, 1999). Topographic depressions were filled and the flow direction was determined from the DEM using ArcView Spatial Analyst (ESRI, 1996). A flow rate of 10 l s^{-1} was used to delineate streams in this particular watershed. Simulations were carried out using daily maximum and minimum temperatures, rainfall, and solar radiation measured at the Domingo farm in the middle of the watershed (76°31′36″ W, 2°47′21″ N; altitude 1659 m) from January 1, 1994 through December 31, 1997 (Luijten, 1999). Basic soil properties such as water holding capacities (at saturation, drained upper limit and wilting point), hydraulic conductivity, and soil depth were derived from existing soil maps and earlier soil analysis in the area (Hansen and Jones, 1996; Revelo et al., 1994).

Land use under the base scenario was based on a classification of a 1989 Landsat 4 Thematic Mapper image (Langford and Bell, 1997), aggregated from 10 to 5 classes (bare soil, pasture, scrub, forest and cropland) and resampled at 100 m resolution. Land use change each year was simulated using stochastic rules for 36 years (1989–2025). Changes were based on relative tendencies to move from one to another land use type, accounting for six characteristics of the landscape: Euclidean distance to roads, distance to streams, distance to houses, terrain slope, elevation and land use of adjacent land units (Luijten, 1999). The relative tendencies were different for each scenario, resulting in different a land use pattern for each scenario

Irrigation water use was based on the water requirements for field-grown tomato, the primary irrigated crop in the watershed, using the CROPGRO v3.5 (98.0) crop simulation model (Boote et al., 1998). Domestic water demand was assumed 150 l day^{-1} per capita under each scenario, 20% higher than in the 1990s (Ramirez, 1992). The method of drinking water supply was assumed the same as in the 1990s: water is tapped from an aqueduct that is filled from three locations in the river (Fig. 2) at a combined rate of 1728 m^3 day^{-1} (20 l s^{-1}). This rate was assumed constant over the year, unless less water was available in the river. Any surplus water from the aqueduct was assumed to leave the watershed unused. Industries were located near the Pan-American Highway and Cabuyal River in the middle of the watershed (Figs. 1 and 2). They used water from the river under the CF and EW scenarios, whereas it was taken from the aqueduct under the BU scenario. As differences in water use are generally greatest between different months rather than between different days within the same month, average water use was assumed equal on all days within the same month.

3. Results

3.1. Simulated water yields with uniform land use

Compared with the base scenario, the hydrological response of the watershed with uniform cropped land was only slightly different. The average base flow index (BFI) and surface run-off are nearly identical (Table 3). Evapotranspiration was 4.6% lower and, consequently, the water yield of the watershed increased nearly 5% with cropped land.

The uniform forest cover gave very different simulation results. Compared to the base scenario, annual ET increased about 13%, caused by the forest's ability to intercept rain and to extract water from deeper soil. Because of the increase in ET, average river flow decreased from 824 to 705 l s^{-1}, base flow decreased from 238 to 184 l s^{-1}, and surface run-off decreased from 154 to 90 l s^{-1} (Table 3). Forest decreased the total water yield compared with the base case.

A bare soil had opposite effects. River flow showed a very erratic behaviour caused by more frequent and heavy surface run-off. The BFI was lower than under the base case (0.612 vs. 0.862), indicating that the relative contribution of surface run-off to river flow increased significantly. ET reduced from 917 to 504 l s^{-1} and average river flow increased from 824 to 1226 l s^{-1}. The minimum and average base flows decreased to, respectively, 191 and 544 l s^{-1}, the lowest values of all three uniform land uses. This suggested that a watershed with a high percentage bare soil has the least ability to sustain a steady flow throughout the year (despite its highest annual river flow). Such steady flow is particularly important in the dry season.

Table 3
Simulated water flows and components of the water balance, before accounting for water use and impedance by dams, for the 1990s base scenario, three uniform land uses and three development scenarios in 2025[a]

Scenario	Mean ET (mm $year^{-1}$)	Average BFI[b] (–)	Minimum base flow (l s^{-1})	Average base flow (l s^{-1})	Average run-off (l s^{-1})	Average river flow (l s^{-1})
Base scenario, 1990s	917	0.813	238	670	154	824
Only cropped land	874	0.818	217	707	157	865
Only dense forest	1038	0.872	189	615	90	705
Only bare soil	504	0.444	191	544	682	1226
Corporate Farming	865	0.808	246	706	168	874
Ecological Watershed	945	0.856	219	681	115	796
Business as Usual	813	0.779	269	721	205	925

[a] Data are averaged over four simulated years.
[b] BFI: Base Flow Index, the ratio of base flow to river flow. The remaining fraction (1−BFI) indicates the contribution of surface run-off to river flow.

3.2. Corporate Farming scenario

Fig. 3 shows the initial 1989 land use pattern and the simulated land use patterns for all scenarios for 2025, and Table 4 gives the corresponding percentages occupied per land use. The percentage cropland increased from 9.0% in 1989 to 26.3% under the CF scenario. It is assumed that only part of the crops is needed for self-consumption, whereas the remainder is marketed. The area pasture, scrub and forest decreased significantly (Table 4). These land uses affected the hydrological response of the watershed: average run-off increased from 824 to 874 l s^{-1} (Table 3). Average annual base flow and surface run-off increased by, respectively, 5 and 9%. These changes are relatively small compared with those under the other two scenarios.

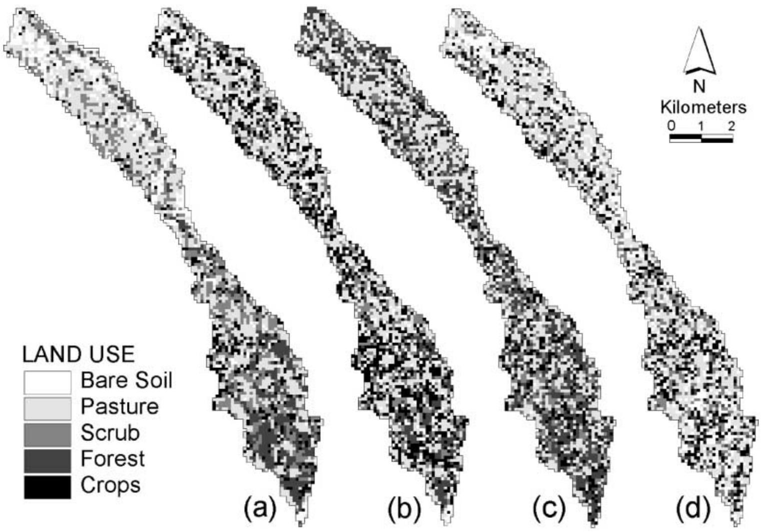

Fig. 3. Distribution of land use in the Cabuyal River watershed. (a) Actual situation in 1989; (b) Corporate Farming scenario; (c) Ecological Watershed scenario; (d) Business as Usual scenario. The grid resolution is 100 m and the total area is 3246 ha.

Table 4
Area covered (in %) and the area per person (in ha, between parentheses) in the Cabuyal River watershed, in 1989 and for simulated land use patterns in 2025

Land use	Initial data (1989 data)	Corporate Farming	Ecological Watershed	Business as Usual
Bare soil	12.1 (0.170)	12.0 (0.130)	4.2 (0.040)	20.5 (0.180)
Pasture	38.3 (0.538)	31.5 (0.344)	36.6 (0.350)	37.1 (0.327)
Scrub	24.6 (0.346)	18.2 (0.199)	15.6 (0.149)	18.1 (0.160)
Forest	16.0 (0.225)	12.0 (0.130)	30.0 (0.287)	5.7 (0.050)
Crops	9.0 (0.126)	26.3 (0.287)	13.6 (0.130)	18.6 (0.164)
Total	100 (1.405)	100 (1.091)	100 (0.956)	100 (0.881)

Simulated water use was as high as 16 328 m^3 day^{-1} in August and September, when irrigation requirements are highest (Table 5). Fig. 4a shows the simulated river flow at the watershed outlet after including all water uses and impedance by dams. Simulated river flow rates varied significantly during the wet season (October through May) as a result of frequent and strong rainfall (Fig. 5). The percentage of water extracted over the 4 years varied between 2.1% in the wet season and 32.1% the end of the dry season (Table 6, Fig. 6a).

The dams sustained a minimum flow of 400 l s^{-1} at the outlet during the dry season (Fig. 6a). Simulated river flow did not immediately increase above 400 l s^{-1} at the beginning of the wet seasons because the first rains of the wet season were used to refill the dams until they reached storage capacity again. If there had been no dams, the maximum percentage of water extracted would have been as high as 61.0%. Thus, dams reduced the maximum percentage of water used during the dry season. To sustain a 400 l s^{-1} flow rate, the combined capacity of the dams was as high as 1725 million m^3 in 1996 (Table 7). This capacity varied per year and depends on the minimum flow rate.

3.3. Ecological Watershed scenario

The percentage forest increased from 16.0 to 30.0% and bare soil decreased from 12.1 to 4.2% (Table 4), reflecting land conservation under the EW scenario. The area cropland per capita (0.130 ha) remained nearly the same as in 1989. Compared with the base scenario, simulated annual ET was higher (945 vs. 917 mm $year^{-1}$) because of the larger area of pasture and forest (Table 3). Consequently, the average river flow was lower (796 vs. 824 l s^{-1}). The base flow index increased to 0.856, caused by the fact that pasture and forest vegetation provided good ground cover and protection against surface run-off. The BFI of the lower and upper parts of the watershed were 0.835 and 0.875, respectively, indicating that surface run-off

Table 5
Estimated water use (m^3 day^{-1}) in the Cabuyal River watershed for the three scenarios in 2025[a]

Water use type	Time of year	Corporate Farming (m^3 day^{-1})	Ecological Watershed (m^3 day^{-1})	Business as Usual (m^3 day^{-1})
Domestic (V_{DOM})[b]	All year	1728 (1035)	1728 (1181)	1728 (1282)
Industrial (V_{IND})	All year	2600	432	259
Irrigation (V_{AGR})	June	9000	3000	2900
	July	9000	4000	4350
	August	12 000	4000	4350
	September	12 000	4000	4350
	October	9000	3000	2900
	Other months	750	0	0

[a] Water use was assumed identical on all days within the same month.
[b] A fixed amount of water was extracted by the drinking water system in each scenario. The values between parentheses are the estimated amounts of water that were actually used for domestic purposes.

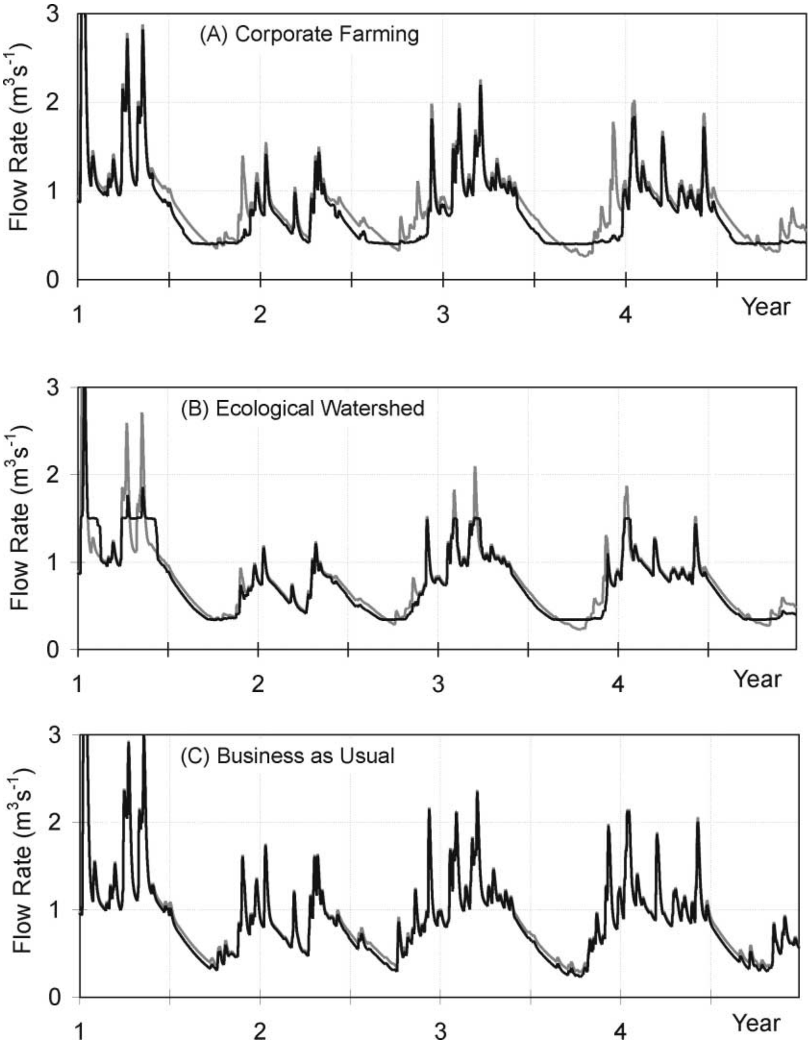

Fig. 4. Simulated river flow before (gray curve) and after (black curve) considering water use and impedance by dams, if any, for the three scenarios in 2025 and a period of 4 years.

contributed more to river flow in the lower part than in the upper part of the watershed.

Simulated river flow rate was kept between the minimum required rate of 350 l s^{-1} and the maximum allowed rate of 1500 l s^{-1} (Fig. 4b), except in January and April of the first year. At three times during those months, between 150 and 200 mm rainfall fell within a few days, resulting in a high surface run-off. The combined storage capacity of the dams was insufficient to adequately reduce the high peak flows that occurred. The lowest and highest percentages of available water extracted were 0.9 and 16.9%, respectively (Fig. 6b, Table 6). The maximum value of 16.9% is

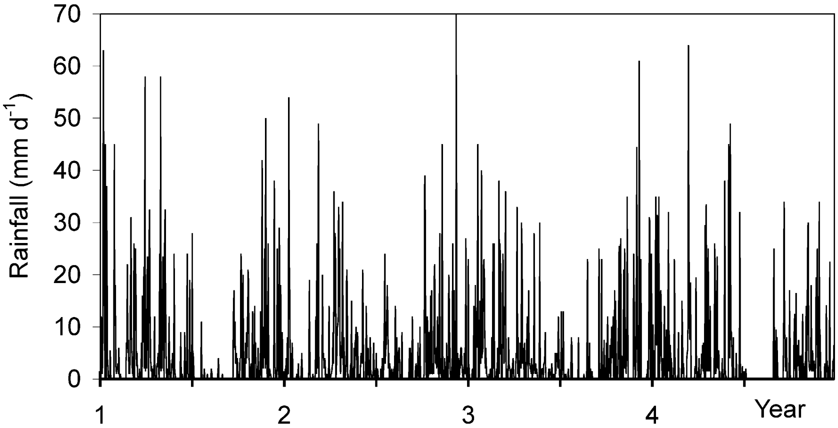

Fig. 5. Measured daily rainfall at the Domingo farm from 1 January 1994 through 31 December 1997. This period is referred to as the years 1 through 4. Annual rainfall in these four years totaled, respectively, 1908, 1642, 1682 and 1556 mm.

the lowest of all three scenarios. Also, it is only a little higher than in 1989 (16.9 vs. 15.5%), despite the fact that irrigation water use increased from 1503 m^3 day^{-1} in 1989 (not shown in Table 6) to 4000 m^3 day^{-1} in the 2025 EW scenario. Again, the dams and the minimum flow requirements are the reason for this. If there were no dams, the highest percentage of water extracted would have increased from 16.9 to 26.2%.

3.4. Business as Usual scenario

The percentage bare soil became very high (20.5%) and forest became very low (5.7%) due to lack of local governance and a resource management strategy. The area cropland per capita increased (0.164 vs. 0.126 ha), which is assumed necessary to compensate for the decreased productive capacity of the soil and lower per hectare yields. The large area of bare soil and its smaller evaporative capacity reduced annual ET to 813 mm $year^{-1}$, lowest of all three scenarios. Annual average surface run-off and river flow were, respectively, 205 and 925 l s^{-1}, highest of all scenarios (Table 3). The average BFI was 0.779 (0.758 for the lower part; 0.799 for the upper part). Thus, surface run-off contributed more to river flow in the EW scenario than in the BU, resulting in a more erratic behaviour of river flow over time and higher potential for erosion (not studied here).

The lowest and highest percentages of water extracted from the river were, respectively, 0.7 and 21.9% (Table 6, Fig. 6c). They were considerably lower than those of the CF scenario because of the lower industrial and agricultural water use (Table 5) and higher stream flow before water extraction (Table 3). Although total peak water use was slightly less for the BU scenario than for the EW scenario (6078 m^3 day^{-1} and 6160 m^3 day^{-1}, respectively), the maximum percentage of water

Table 6
Summary of the water supply and water demand for the situation in the 1990s and the three scenarios in 2025

Water class	Initial, 1990s (Vol. water, m^3 day^{-1})		Corporate Farming (Vol. water, m^3 day^{-1})		Ecological watershed (Vol. water, m^3 day^{-1})		Business as Usual (Vol. water, m^3 day^{-1})	
	Min[a]	Max[b]	Min	Max	Min	Max	Min	Max
Domestic water use	329	329	1035	1035	1181	1181	1282	1282
Surplus drinking water	1399	1399	693	693	547	547	187	187
Industrial water use	102	102	2600	2600	432	432	259[c]	259[c]
Irrigation water use	0	1503	750	12 000	0	4000	0	4350
Change storage dams	N/A	N/A	0	−28 510[g]	0	−15 578[g]	N/A	N/A
Net water extraction[e]	1728	3231	5078	16 328	2160	6160	1728	6078
River flow before use[d,h]	240 000	21 514	240 000	22 378	240 000	20 822	240 000	27 734
River flow after use[d]	238 272	18 181	234 922	34 560	237 840	30 240	238 272	21 656
% Extracted[f]	0.7	15.5	2.1	32.1	0.9	16.9	0.7	21.9

[a] Data in the 'Min' columns are those for the day with lowest water use and a high water supply, resulting in the lowest % extracted.
[b] Data in the 'Max' columns are those for the day with highest water use and a low water supply, resulting in the highest % extracted.
[c] Water for industrial use taken from the drinking water system. Surplus intake by the drinking water system is reduced accordingly.
[d] Use includes actual water use (domestic, industrial and agricultural) and the effect of dam operation on stream flow.
[e] Water extraction from river. If there are dams, actual water use may be different depending on changes in the storage in the dams.
[f] Calculated as (net water extraction) / (river flow before use−change dams in river).
[g] Negative values indicates water release from dams to meet minimum flow requirements after water use.
[h] The values of 'River flow before use' listed in the 'Min' columns have been set at 240 000 m^3 day^{-1} (2778 l s^{-1}) in all four situations.

extraction was considerably larger (21.9 and 16.9%, respectively), caused by absence of dams.

4. Discussion

4.1. Implications of development in the Cabuyal River watershed

Several assumptions were made for this study. Dams were distributed ideally and evenly throughout the watershed and were assumed to function properly. A perfect infrastructure for water transport to the industrial and agricultural end users was assumed. All households in the administrative Cabuyal region were assumed to have access to a drinking water system (presently only 85% of the households), and these systems supplied enough water all year. No limitations or technical difficulties in extracting water from the river and applying it for irrigation were considered. We

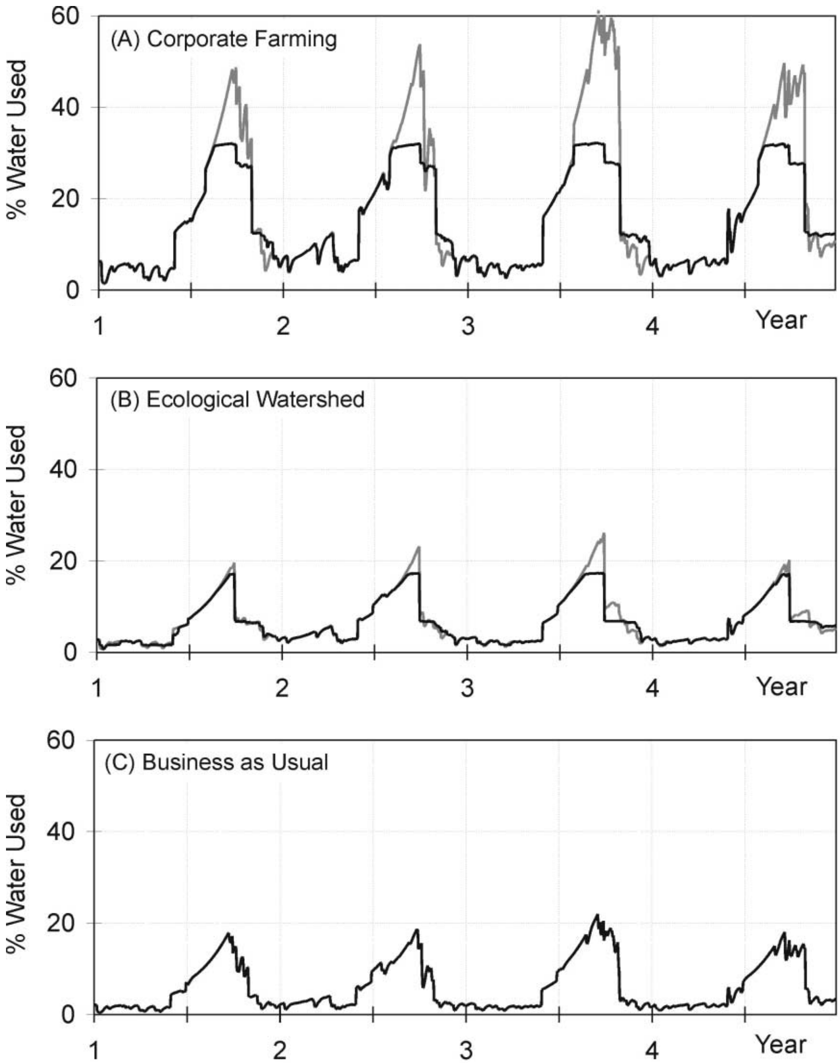

Fig. 6. Simulated percentage of river flow that is extracted for direct use or refilling of dams, without (gray curve) and with dams (black curve), if any, for three scenarios in 2025 and a period of 4 years. There were no dams in the Business as Usual scenario.

did not consider in situ use of water for recreation, fisheries or dilution of any industrial contaminants because these water uses are currently not priorities in the watershed.

Simulation results do not prescribe a critical or an ideal pathway for development. They should be used to negotiate specific desired future conditions for local rural development. The Cabuyal River watershed has the potential to meet the anticipated increase in water use under each explorative scenario. Current water-related problems

Table 7
Required combined storage capacity of dams to supply irrigation water and sustain minimum flow rates (after water use) for the 2025 Corporate Farming scenario and for five different minimum flow rates

Minimum flow (l s^{-1})	300 (Vol., in 1000 m^3)	350 (Vol., in 1000 m^3)	400 (Vol., in 1000 m^3)	450 (Vol., in 1000 m^3)	500 (Vol., in 1000 m^3)
Year 1 (1994)	231	464	779	1193	1638
Year 2 (1995)	277	424	741	1133	1601
Year 3 (1996)	933	1320	1725	2170	2671
Year 4 (1997)	444	768	1133	1534	1983

in the watershed seem to be related to water management practices, rather than the amount of available water. Current practices do not provide much leeway for increased water use in the future, but they are correctable. For example, many problems and conflicts associated with water security are related to the insufficient supply of drinking water during the dry season, which is caused by the use of large amounts of potable water for irrigation. It may be necessary to provide farmers with financial and/or technical assistance for exploiting other means of irrigation, in particular by pumping directly out of streams or by collecting water run-off in small dams or irrigation ponds.

Extraction of over 61% of the available water in the CF scenario if there were no flow control, is worrisome and could become a serious problem. This percentage was based on the assumption of an average daily water use. Such a high figure raises concerns about effects on aquatic and riparian ecology, concentrations of potential contaminants, water reserves for especially low rainfall years (for example, El Niño episodes), and the watershed resilience to meet temporarily higher water needs during the day or extreme levels of water demand. Construction of dams seems the best method for supplying sufficient irrigation water without endangering the supply of water to downstream water users. There are currently no plans for a dam in the watershed. However, planners in another and larger watershed north of Cali finalized plans for the construction of a dam with a capacity of 18 million m^3 to support some 50 000 families (E.B. Knapp, 1999, personal communication). This dam capacity is equivalent to 0.45 million m^3 to support the 1250 families in the Cabuyal River watershed, which compares well with calculated capacities for the 300 and 350 l s^{-1} flow thresholds in Table 7.

Many local farmers consider forests as 'water producers' and believe that the upper watershed tributaries determine the water flow in the Cabuyal River (Knapp et al., 1999). They have been concerned that deforestation reduces availability of stream water, and participatory projects were carried out to create protective forest areas around streams and springs (Ashby et al., 1996). Simulation results indicated, however, that the lower and upper parts of the watershed contributed equally to stream water (although they somewhat differ in *how* they contribute to river flow, i.e. through surface run-off or base flow). Calder (1998) and Hamilton (1985) noted that it is often incorrectly thought that forests increase total water yield. Of course, reforestation will improve ground cover and may, consequently, result in less surface run-off and less erratic river flow. While few will argue the benefits of deforestation activities, there is yet no scientific evidence that this will result in more river water in this particular watershed.

4.2. General applicability of the model

SWBM helped reduce some of the complexity associated with the interdependencies between land and water resources, spatial linkages within the watershed, as well as basic water budgets. Results of this study can help multi-institutional alliances to become proactive and perform some of the critical functions that were identified by Ravnborg and Ashby (1996): (1) identifying stakeholders and ensuring their representation in management efforts; (2) providing forum for analysis and negotiation of diverse interests; (3) defining rules and norms for the use of resources within the watershed; (4) initiating a process of local-level resource monitoring research; (5) formulating and exerting demand for services from external institutions in support of local management efforts; and (6) negotiating internal versus external watershed interests.

The Cabuyal River watershed case study demonstrated the potential of SWBM. The model is generic and it has now been adopted by the International Center for Tropical Agriculture (CIAT), Cali, Colombia, to other watersheds in Latin America. For example, another water security study was carried out for the 12 100 ha Tascalapa watershed in Honduras, and results were integrated in the Honduran Community Based Decision Support System tutorial (Swindell, 2000). There are no stringent restrictions on the application of SWBM, however, Luijten et al. (2000a) suggested that the model can best be applied to watersheds with an area in the order of 50 000 ha or less, and that a maximum grid size of 50–100 m should be used.

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