# A TOOL FOR COMMUNITY-BASED WATER RESOURCES MANAGEMENT IN HILLSIDE WATERSHEDS

By

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This study presents a tool for community-based water resources management in hillside watersheds. A simulation-based methodology was developed for assessing water scarcity on a watershed scale. The Spatial Water Budget Model was developed for simulating water supply and demand and analyzing temporal and spatial variations in overall water balance and in stream water flow due to changes in land use, population and industrial development.

Daily domestic, industrial, and agricultural water demands for the period 1994-1997 were quantified for the Cabuyal River watershed in southwest Colombia. Simulated flow rates in the river compared well to measured flow rates and varied considerably over space and time. The 4-year average annual simulated flow rate was 824 L/s, but it dropped below 300 L/s in the dry season and more than doubled during periods of heavy rainfall. Base flow contributed more to river flow in the upper part of the watershed than in the lower part, 86.7% and 75.9% respectively, due to differences in land use. Although simulated water

availability was at its lowest during periods when water was needed most, the river still supplied sufficient water to meet all water demands on any day from 1994 through 1997.

Three different scenarios and their implications on water scarcity in the Cabuyal River watershed in the year 2025 were analyzed: Corporate Farming, Ecological Watershed, and Business as Usual. Different land use, water demand, demographics, and presence of dams characterized each scenario. A plausible land use pattern for each scenario was created with a rule-based land use change model. The percentage of the area covered by each land use type was significantly different for each scenario.

Simulation results suggested that the watershed has the potential to meet anticipated increases in water use under all three scenarios, although up to 61% of the river flow was used in the dry season under the Corporate Farming scenario if there were no dams. Current water management practices in the watershed do not provide much leeway for increased water use. Simulation results indicated specific water management measures that could be taken. For example, dams with a volume of about 0.5 - 1 million $m^3$ could be built to supply enough irrigation water and maintain flow rates of 350 L/s. Because of their limited capacity, current drinking water systems should be used for domestic purposes exclusively.

# CHAPTER 1
# INTRODUCTION TO COMMUNITY-BASED WATERSHED MANAGEMENT

## The Importance of Water

For many years water has been considered to be a plentiful resource in most areas, amounting virtually to a free good. The situation is now rapidly changing to the point that, particularly in the more arid regions of the world, water scarcity has become the most important threat to food security, human health, and natural ecosystems. An estimated 1.4 billion people, amounting to a quarter of the world's population, or a third of the population in developing countries, live in regions that will face *severe* water scarcity by 2025 (Seckler et al., 1999). Over one billion people live in arid regions that will face *absolute* water scarcity by 2025. These regions do not have sufficient water resources to maintain 1990 levels of per capita food production from irrigated agriculture, even at high levels of irrigation efficiency, and also to meet reasonable water needs for domestic, industrial, and environmental purposes by 2025. Competition for the limited amount of fresh water resources and conflicts about its use is likely to increase.

The hillsides agro-ecosystem of Latin America covers about 1 million square kilometers, and is the basis of livelihood for an estimated 20 million people. Principal countries include Bolivia, Colombia, Costa Rica, El Salvador, Ecuador, Peru, Venezuela, Guatemala, Honduras and Nicaragua (CIAT, 1996). Some basic statistics on population size and fresh water availability in these countries are given in Table 1-1. An estimated half of the hillside ecosystems in these countries is progressively deteriorating as a consequence of the combined effects of deforestation, overgrazing, destructive tillage techniques, improper water management and unfavorable socioeconomic conditions (Knapp et al., 1999). This seriously threatens the food security of the already poor people in rural communities in these regions.

Several studies have recently been conducted to quantify water fresh water availability and water scarcity at a global or national level. In these studies, countries were ranked according to the per capita available “Annual Water Resources” (AWR). Falkenmark et al. (1989) considered fresh water shortages local and rare for AWR values above 1,700 $m^3$ per capita, whereas water was considered a primary constraint to life for AWR values less than 500 $m^3$ per capita. Alternatively, Raskin et al. (1997) considered water scarce when more than 40% of the AWR was withdrawn. Seckler et al. (1998) also used an AWR approach, but applied it to both low and high irrigation efficiency scenarios for 2025.

Global per capita AWR is currently about 7,870 $m^3$ (Seckler et al., 1998), more than four times the threshold 1,700 $m^3$. Table 1-1 lists the AWR for a number of Latin American countries that have a high percentage of steep-slope agriculture. For all countries in Table 1-1 except Peru, per capita AWR exceeds the threshold, suggesting an abundance of available fresh water in these countries and enough leeway to expand water use in the future. However, water availability is distributed in a spatially heterogeneous manner in patterns that differ from water needs, that is, regions that have much water may need it least, and vice versa. The AWR data in Table 1-1 do not give information on water availability on spatial scales smaller than a country, for example, a watershed. Water availability may differ considerably between different watersheds in a country or between different communities within a watershed. This is the case in the Cabuyal River watershed in southwest Colombia (Figure 1-1). This watershed represents a group of watersheds in which warning signs of reduced water availability have been observed, even though the AWR value of the nation as a whole seems to be fine.

This chapter is a comprehensive introduction to a dissertation research that focused on water management in the Cabuyal River watershed, and in particular analyzed the implications of various paths of future development on watershed availability in the watershed. First, I discuss different uses and interpretations of *watershed* and *management*, and the involvement of local communities. This is primarily based on a literature review. Secondly, water management in the Cabuyal River watershed is set out in detail, discussing the water supply system, water-related problems and conflicts, and the organizations that are involved in water management. Thirdly, a research framework for assessing water scarcity is set out and an outline of the dissertation is given.

Table 1-1. Basic statistics on population and water availability in Latin American countries that have a high percentage of steep-slope agriculture.

| Country | Steep area[1] (percent) | Population[2] (million) | AWR[3] ($km^3$) | Per capita AWR ($m^3$) |
|---|---|---|---|---|
| Bolivia | 40% | 8.33 | 300 | 36019 |
| Colombia | 40% | 38.91 | 1070 | 27503 |
| Costa Rica | 70% | 3.80 | 95 | 25013 |
| El Salvador | 75% | 6.32 | 19 | 3007 |
| Ecuador | 65% | 12.65 | 314 | 24830 |
| Guatemala | 75% | 12.22 | 116 | 9491 |
| Honduras | 80% | 6.49 | 63.4 | 9776 |
| Nicaragua | 80% | 4.69 | 175 | 37282 |
| Peru | 50% | 25.66 | 40 | 1559 |
| Venezuela | 70% | 24.17 | 1317 | 54489 |

[1] Percent of the area under agriculture with slopes > 30%. Source: CIAT (1996).
[2] Estimated 2000 population according to United Nations (1998) medium growth projection.
[3] AWR = Annual (fresh) Water Resources. Source: Seckler et al. (1998).

# Terminology in Watershed Management

## The Watershed Ecosystem

A *watershed* in a hydrological sense is a synonym for *drainage basin* or *catchment area*. It refers to the total land area above some point (usually somewhere in a stream) from where water collects and flows downhill to a common outlet (Black, 1996). Watershed boundaries can be unambiguously delineated from topography and the location of streams channels, and mostly do not coincide with boundaries of administrative units like provinces, communities or villages.

Watersheds can be aggregated. Any watershed that does not directly drain into the sea or a lake is part of a larger watershed. For example, the administrative Cabuyal region includes the entire Cabuyal River watershed and parts of the Guaicoche River, Pescador River, and Ovejas River watersheds (Figure 1-2). The three smaller rivers merge into the Ovejas River, which is a direct tributary to the Cauca River, one of the Colombia's largest rivers.

On the other hand, if the stream network in a watershed consists of multiple branches (a branch is a single stream channel without junctions), then the watershed can be split up into smaller watersheds. The number of sub-watersheds cannot exceed the number of stream branches. Figure 1-3 illustrates the delineation of sub-watersheds. The sub-watersheds in Figures 1-3 A, B, C, and D were delineated from different stream networks with minimum contributing areas to streams of 500, 150, 40 and 10 ha, respectively. A lower threshold results in more streams and more sub-watersheds. It is possible that sub-watersheds are smaller than the thresholds (the thresholds apply to the streams, not to the sub-watersheds).

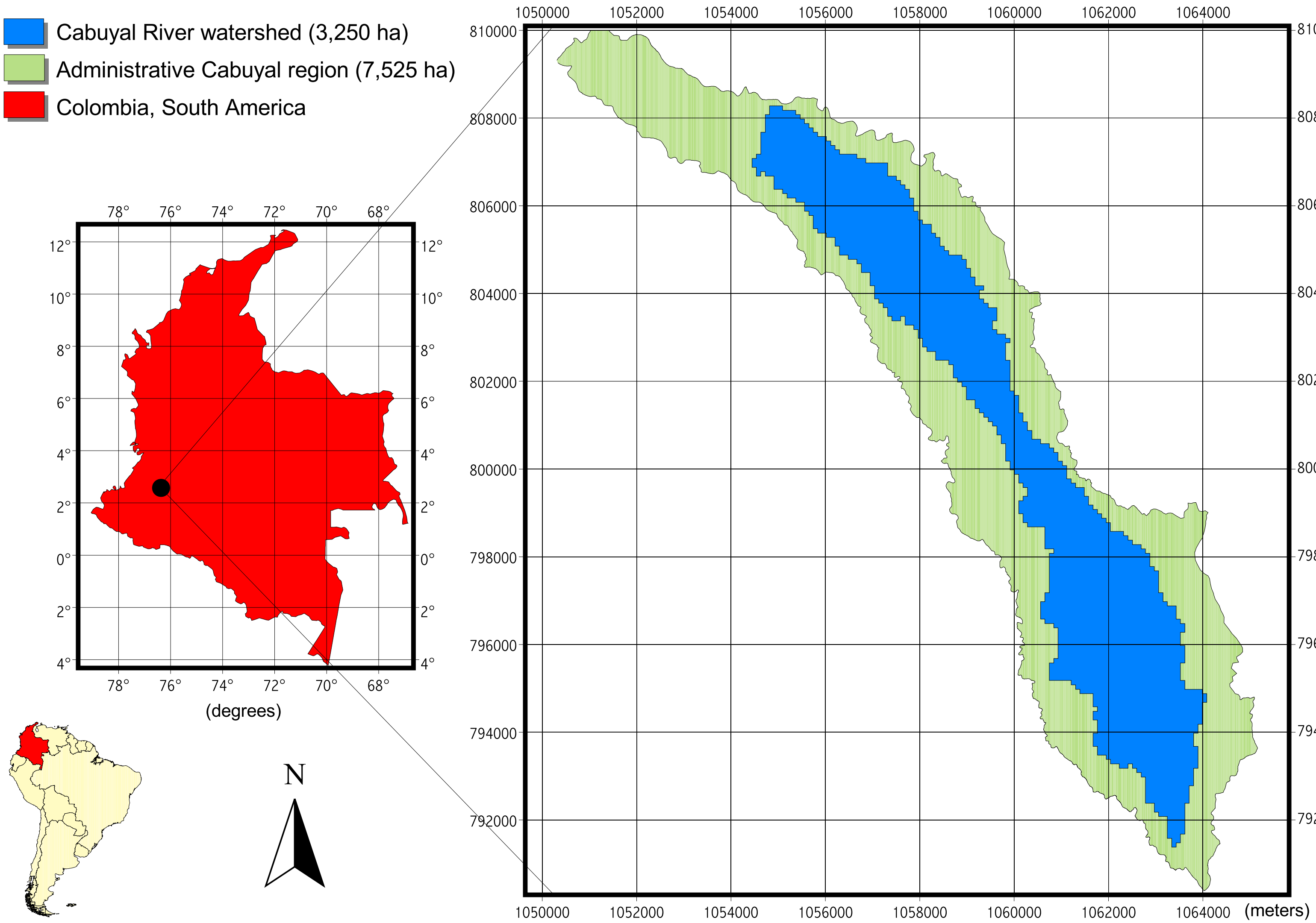



Figure 1-1. Location of the Cabuyal River watershed in southwest Colombia.

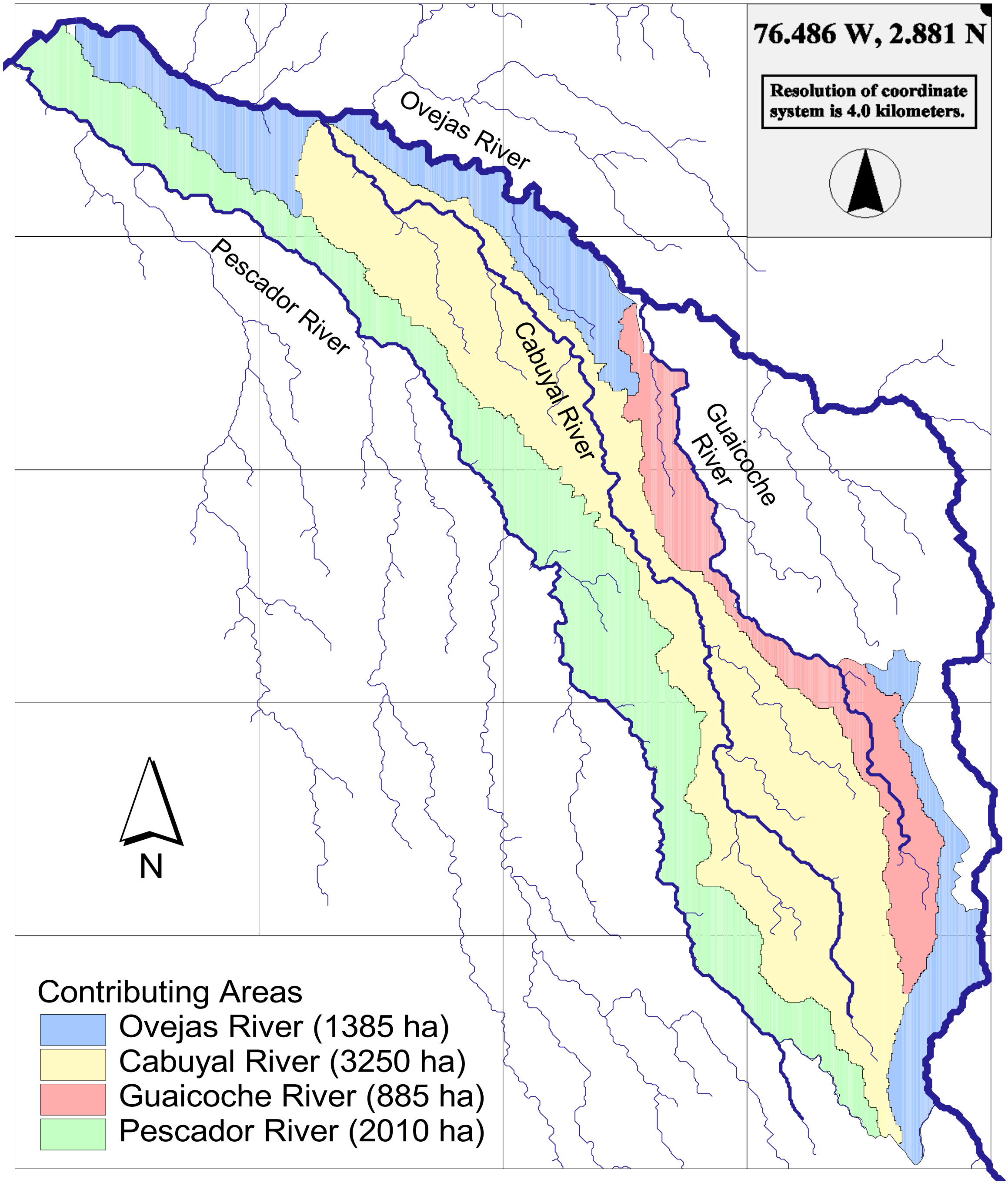



Figure 1-2. Division of the 7,525 ha administrative Cabuyal region into areas that directly contribute to the Ovejas, Cabuyal, Guaicoche, and Pescador Rivers. The rivers form most of the boundaries of the administrative Cabuyal region.

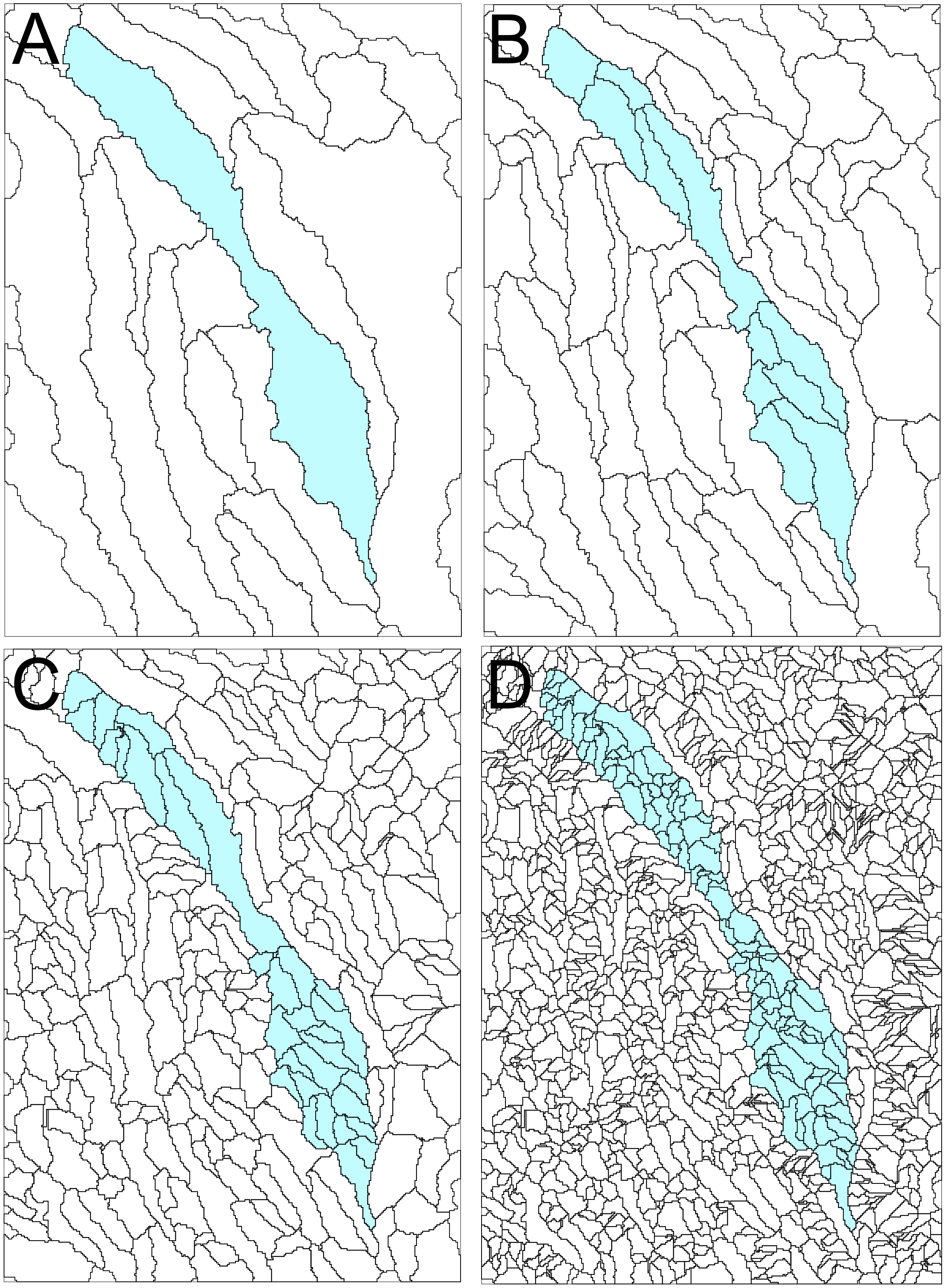



Figure 1-3. Boundaries of sub-watersheds within a 14.5 by 20 km area around the Cabuyal River Watershed (blue colored), as delineated from streams that have minimum contributing area of 500 ha (A), 150 ha (B), 40 ha (C) and 10 ha (D).

Typical research programs that operate at watershed scale include storm water runoff and drainage control, flood plain management, reservoir and dam control, understanding movement of pollutants in the groundwater, and prevention of erosion and sedimentation. These research programs focus on the hydrological function of watershed, that is, the collection, storage and discharge of water and any nutrients and soil particles carried by the water.

Watersheds also have an ecological function (Black, 1996). It is important to recognize the human and biological activity within watersheds. Watersheds provide the basis of livelihood for communities and their members—they live there, grow crops, use water, and use wood for fire and construction. Watersheds are also the natural habitat for animals and other biological species, and function as an environmental filter. Hence, I define a watershed as a *"complex and dynamic ecosystem in which natural processes occur, agricultural and/or industrial activities take place, and people interact with each other and with their natural environment*, *and the boundaries of which are based on topography and the location of stream channels.*"

Watersheds, like many other natural and biological systems, are hierarchically organized and can be studied at a number of levels. Figure 1-4 illustrates the hierarchical structure in a landscape with multiple watersheds and communities. Farms, households and industries form the base of the hierarchy because the different activities and enterprises at these levels are the users of water and land resources. The divisions into communities and watersheds are independent and typically do not coincide. In the Cabuyal River watershed, for example, streams function as boundaries between communities and as boundary for most of the administrative watershed. Consequently, almost every sub-watershed (except the very small ones) is located within the boundaries of two or more communities.

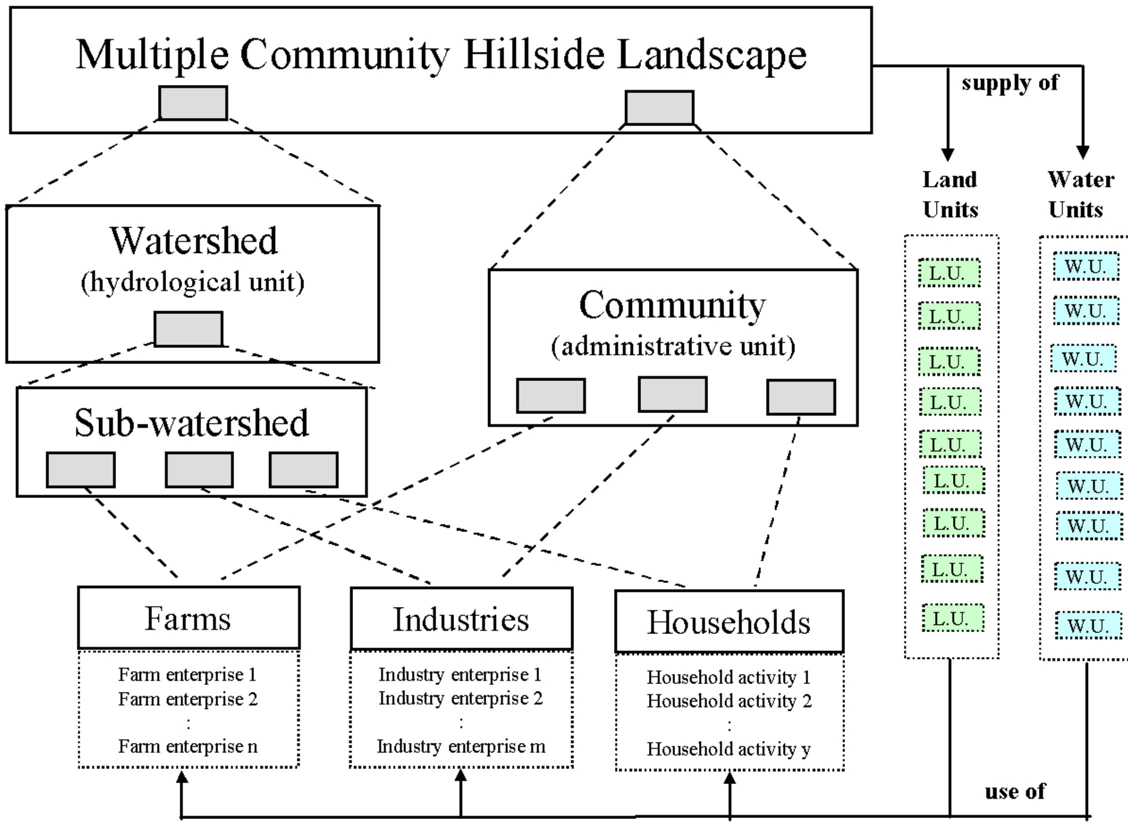



Figure 1-4. Representation of the hierarchical structure of a multiple community hillside landscape. Farms, households and industries form the base of the hierarchy.

Watersheds consist of different components like communities, people, soil, water, farms, houses, industries and organizations. These components exist in association with one another and interact with their biophysical and socioeconomic environments, that is, everything external to the watershed. Watersheds are dynamic and adaptive systems, which change due to natural and human-induced processes. Some processes have relatively low impacts on watersheds, whereas others may temporarily or permanently alter watershed components. Natural ecosystems are assumed to generally function around a dynamic equilibrium state or multiple stable states (Holling, 1986). People may respond to the state of the watershed systems by taking management actions or changing policies or rules that force the system to move towards another state.

Watershed Management

Watershed management refers to the integrated management of a multitude of resources such as crop land, pasture, forests and water to each of which a multitude of often conflicting interests relate (Knapp et al., 1999). It involves decisions on the conservation, regulation, and allocation of resources (Hanna, 1995). Conservation decisions are made to guide and limit resource use in order to preserve the quantity and the quality of that resource over time. Regulation decisions affect the rate, timing and technology of resource extraction by the various users. Allocation decisions determine how a limited quantity of a resource is being divided among competing resource users. Specific water-related management activities include storm water runoff and drainage control, water reservoir and dam control, minimum stream flow control, peak flow reduction, reduction of sedimentation in stream channels, improvement of irrigation efficiency, and equitable water allocation among water users. Land-related management activities include prevention of soil degradation, erosion control, and development and implementation of new tillage techniques. And forest-related management activities include (controlled) deforestation and reforestation.

Watershed management activities take place and humans interact with others and with nature according to institutional arrangements. An institution is not a synonym for an organization in the narrowest sense of an administrative unit. I define a watershed management institution as "*a set of formal and informal norms, laws, rules, rights, sanctions and conflict resolution mechanisms, designed and applied to manage and control the supply, allocation, and use of watershed resources, and the processes by which these shift and change*." Resource management institutions have been extensively discussed in the literature (e.g. Bromley, 1989; Ostrom, 1990; Ostrom et al., 1993; Hanna and Munasinghe, 1995; Singleton and Taylor, 1992).

A central theme in literature on resource management and institutions is the "Tragedy of the Commons" (Hardin, 1968). It refers to a possible fate of resources that are not owned by anyone and accessible to everyone, the so-called open access resources. It has been generally agreed upon that open access resources are highly susceptible to over-use and degradation as a consequence of each user's incentive to use as much as possible, or at least, use it before others do (McKean, 1992; Ostrom 1990; Roberts and Emel, 1992). The tragedy of the commons illustrates that the absence of institutional arrangements, as well as ill-defined and non-enforced institutions, may have a strong adverse affect on the state of the resources in a watershed.

Watersheds have been widely recognized as an appropriate biophysical or socio-economic unit for management of water resources (Lal, 1999; Rhoades, 1998; Brooks et al., 1997). The United Nations Conference on Environment and Development (UNCED) named the watershed as the unit of analysis for integrated water resources management in Agenda 21 (McKinney et al., 1999). Virtually all major development organizations, ranging from the World Bank to small local NGOs, are promoting watershed management in hundreds of communities throughout the world (Rhoades, 1998). Agricultural research centers like the International Center for Tropical Agriculture (CIAT) and the International Water Management Institute (IMWI) have adopted the watershed as a useful unit of organizing research and development activities (Knapp et al., 1999; McKinney et al., 1999). These projects are generating a large number of publications and conference proceedings (Lal 1999; McKinney et al., 1999; Batchelor et al., 1998).

Two important aspects make watersheds suitable spatial units for water management. First, the outlet of the watershed is not only the point towards which all water flows, it is also the point that accumulates the effects of land and water management activities. These effects are often deferred to those not directly involved in these activities. Watersheds thus provide a vehicle to consider the critical linkages between upstream and downstream effects, and on-farm and off-farm effects. Secondly, a watershed is a spatial scale that is readily appreciated by policy makers and planners, and offers a reasonable compromise between the small units of farmers' fields and a larger units such as a landscape (Rhoades, 1998). The watershed is a useful scale to which both local stakeholders and policy makers can relate. This makes it an ideal unit to balance production and conservation over both the long and short term planning horizons, address multiple-stakeholder resource issues, and to assess the impacts of human intervention (e.g., extraction and pollution of water, and construction of dams) on the quantity and quality of available water.

## Involvement of Local Communities

A community may be thought of as a group of people living together in a village or another spatial unit based on an administrative division. Specific landmarks such as roads or streams may form the boundaries of communities. This classification of a community is rather restrictive because it does not consider any other factors that may be important. A group of people may also form a community because they are attached to each other by common characteristics in relation to ethics, religion, language, beliefs or other cultural aspects (Agrawal, 1997). In addition, community members usually share a set of common or open access resources. Communities have a more-or-less stable set of members who can be expected to interact with one another for some time (Singleton and Taylor, 1992).

Local communities and their members are frequently involved in resource management and conservation activities (Rhoades, 1998). Community members may help identify when and where problems arise, implement management techniques, or be actively involved in resource use monitoring. For example, in the Cabuyal River watershed, local farmers were involved in establishing live barriers to protect water courses and reduce soil erosion on steep slopes (Ashby et al., 1996). The reason for their involvement was to achieve a trade-off (between effectiveness of conservation practices and their utility to farmers) that was acceptable to farmers, and thereby improved the overall acceptability of conservation techniques. Whereas it is argued that there are few viable alternatives to community-based management and conservation (Wells and Brandon, 1992; Agrawal, 1997), community involvement is no absolute guarantee for successful resource management projects (Ostrom, 1992).

Both theoretical foundations and practical evidence has become available on the importance of strong community structures and active involvement of communities in resource management and conservation. Singleton and Taylor (1992) argue that community involvement is characterized by low transaction costs, that is, all expenses to gather information, identify possible solutions, negotiate agreements, design regulations, coordinate participants, monitor conditions and enforce regulations. Ostrom (1990) noted that the actual use of water and land resource units takes place by individuals at the level of industry and farm enterprises and household activities. Community-level institutional arrangements will have the most influence on the activities of these individuals rather than those imposed from national and regional levels. It is more likely that resource users believe and act according to what a knowledgeable local individual or community leader says, than a state official who is not as familiar with the specific local conditions (Singleton and Taylor, 1992; Ostrom et al., 1994). Community management promotes democracy and equity because it gives members of the community an opportunity to directly share in the decisions about how their resources are used and share in the benefits that are gained from their use (Renard, 1991; Ostrom et al., 1994). Agrawal (1997) argued that the short distance between community members facilitates the immediate discussion and resolution of problems. A larger geographical area or spread of the community implies slower communication, not only because of the actual distance, but also because larger and more bureaucratic organizations may be involved.

Based on experience with local stakeholders in the Cabuyal River watershed, Ravnborg and Ashby (1996) identified six functions that are considered essential to local-level watershed management organizations. These functions are: (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.

## Water Management in the Cabuyal River Watershed

### Characterization of the Watershed

The Cabuyal River watershed is located between 76.63° - 76.49° W and 2.70° - 2.88° N in the Cauca department in southwest Colombia (Figure 1-1). This watershed is one of the primary research sites of the International Center for Tropical Agriculture (CIAT). It is a good example of the difference in scale between catchment boundaries and administrative boundaries: the administrative area of the Cabuyal region contains 22 communities and is 7,525 ha, but the catchment area of the Cabuyal River is only about 3,250 ha. A total of 5,357 people were living in the administrative Cabuyal region in 1995 (de Fraiture et al., 1997).

The topography in the watershed is very steep. Elevation ranges from 1,175 to over 2,200 m and nearly half this area has slopes greater than 30 degrees with slopes up to 75 degrees. The landscape is highly heterogeneous with many small plots of natural forest, bush scrub, pasture, coffee plantation, and various subsistence and cash crops (Langford and Bell, 1997). This highly fragmented landscape is characteristic of most hillsides in Latin America and the Caribbean. Production of a variety of subsistence and cash crops by small farmers is the main activity in the watershed. Industrial activity is limited to processing of cassava in small plants and coffee at farms.

The Cabuyal River and its many small tributary streams supply the water to serve the needs of households, farms, and local industries within the catchment. There is no stream inflow or surface run-on from neighboring regions. All water in the Cabuyal River originates from natural springs and surface runoff within the watershed, i.e. where the people live. This is an important feature of this watershed, as well as for many other hillside watersheds throughout Latin America and the Caribbean. The flow rate in the river varies significantly over space and time. The average annual flow rate of the river is about 1000 L/s (at the watershed outlet), but it can easily double after strong rain events, whereas it decreases to just 250-300 L/s during the dry months of August and September (de Fraiture et al., 1997).

Part of the water of the Cabuyal River is diverted into small pipes to provide clean drinking water to the majority of the households. These networks of pipes are referred to as drinking water systems, locally known as *acueductos*. A total of 9 drinking water systems exist in the administrative Cabuyal region, with capacities varying from 1 to 10 L/s (Table 4-3). Some families do not have access to a drinking water system and use private wells to get water during the dry season. However, water supply by wells is negligible compared to water supply by the river and streams (de Fraiture et al., 1997). This is another important feature of this watershed.

Watershed Management Organizations

Cropland, pasture, forests and water are managed resources in the Cabuyal River watershed. In the late 1980s and early 1990s, the inhabitants of the watershed were confronted with a bewildering number of governmental and non-governmental organizations that were involved in some way in the management of watershed resources (Ravnborg and Ashby, 1996). These organizations had their own and often, from a watershed management point of view, contradictory programs. The following organizations were the main ones.

FEDECAFE (*Federación Nacional de Cafeteros—National Coffee Federation*) is the autonomous and powerful federation of Colombian coffee producers that provides technical assistance and credits to coffee producers. The CVC (*Cooperación Valle de Cauca—Cauca Valley Corporation*) is a large organization with the mandate to manage water and land resources in the Cauca River watershed. Specific CVC activities included hydroelectric power generation, supply of irrigation water, flood control projects, and supply of permits needed for land clearing and burning (Ashby, 1985). ICA (*Instituto Colombo Agropecuario—Colombian Agricultural Livestock Institute*) is part of the Colombian Ministry of Agriculture. Their role has been limited to the provision of technical assistance and credit, exclusively to farmers who want to implement specific recommendations and guidelines of the FEDECAFE and CVC (Ashby, 1985). JACs (*Junta de Accion Comunataria--Community Action Group*) are community-level organizations that integrated and harmonized activities of people within a community (Baptiste, 1994). These organizations administered and assisted in meeting local needs for education, health care, water management, housing, infrastructure, agricultural production, labor, cultural activities, reforestation, and other conservation practices. JAAs (*Junta Administradora del Acueducto-—Local Aqueduct Committee*) were responsible for the management of the drinking water system, which includes maintenance, repair of minor damages, and the collection of water fees (de Fraiture et al., 1997). In addition to these main organizations, there were various minor groups based on indigenous skills, religion, profession, and sex. Despite the fact that such groups are relatively small, generally with no or low budget, and without any official status, they may all affect decisions on resource management. A detailed listing of all organizations and their function is given by Ravnborg and Ashby (1996) and CIAT (1993).

To better address multiple conflicting interests and improve coordination between the many organizations, the inter-institutional consortium CIPASLA (*Consorcio Interinstitucional para una Agricultura Sostenible en Ladera)* was created in 1993 (Ravnborg and Ashby, 1996). The working area of CIPASLA is restricted to the Cabuyal River watershed. CIPASLA consists of three committees. First, an Inter-Institutional Committee, with the mandate to better plan and coordinate the activities of participating organizations and strengthen their ability to support the communities. Secondly, the Watershed User Committee (FEBESURCA (*Federación de Beneficiarios de la Subcuena de Cabuyal*), with the mandate to provide information about the needs of communities and their members and to support the formulation of projects in communities. In 1996, eighteen out of 22 communities have a representative in FEBESURCA. The third committee is the Coordinating and Technical Committee (Ravnborg and Ashby, 1996), which coordinates activities of all organizations and provides technical assistance with the implementation of management and conservation activities. CIAT has an advisory and supporting role in this committee.

## A Decade of Increasing Water Problems

Local stakeholders have identified the decrease of the production capacity of water, soil and forest resources as one of the major problems in their watershed (CIAT, 1993).

Reduced or insufficient water availability during the dry season was recognized as a serious problem. It constitutes an immediate health threat to the population and crop loss may occur if no irrigation water is available. Competition for water and conflicts between and within communities about water use has increased during the last decades (de Fraiture et al., 1997; Ravnborg and Ashby, 1996). Local stakeholders have expressed concern about the negative effects of certain land use changes (in particular deforestation) and lack of adequate soil conservation techniques on the hydrological response of the watershed. They are also concerned about the consequences of decreasing water yield and unregulated water extraction on water availability (de Fraiture et al., 1997). Local farmers argue that river flow has generally become less predictable and that higher peak flows occur. This also increases the risk for flooding of riverbanks, erosion, crop loss and possible damage to any equipment and small dams that may be located in the river.

Most water problems occur in the middle and lower parts of the watershed. Although downstream communities have the advantage of benefiting from a larger catchment area and thus higher stream flows, they also experience the greatest effects of any changes in land and water use that occur at higher elevations. Downstream communities argue that deforestation in the higher part of the watershed has contributed to the decrease in river flow, and that they have less water available for irrigation because communities in the upper part of the watershed extract too much water (de Fraiture et al., 1997; Ravnborg and Ashby, 1996). Consequently, they are experiencing longer periods of drought stress, which increases the risk for crop losses.

Another problem is related to the misuse of the drinking water systems. Some farmers illegally use water from the drinking water system to irrigate vegetable crops during the dry season (de Fraiture et al., 1997). This practice is generally cheaper and less cumbersome than taking water from the river, however, it can significantly reduce drinking water availability for families in lower laying communities. In the dry summer of 1996, the drinking water system ran dry in the community of El Socorro in the lower part of the watershed (Ravnborg and Ashby, 1996). This caused an immediate health threat the people in these communities.

Cassava processing industries are potential sources of water contamination. Although the local population has expressed concern about the effects of decreasing water quality on human and animal health (CIAT, 1993), preliminary water quality analysis did not indicate significant water contamination (de Fraiture et al., 1997). However, if industrial activity expands, significant amounts of stream water may be used to wash and process agricultural products. This processing water is typically returned to the river. This may result in water contamination and increase biological oxygen demand, which may cause a human health risk and threatens *in situ* use of the river for fishery activities (de Fraiture et al., 1997).

Water resources in the watershed can be characterized as open access resources from which everyone can use virtually unlimited amounts. Despite the involvement of many management organizations, institutional arrangements for water use are not effective. Stream water is really an open access resource. The Colombian Water Law states that one is owner of a water source if it originates and dies on one's property (de Fraiture et al., 1997). However, this is not the case anywhere in the watershed and there are no regulations whatsoever about the use of stream water. The local aqueduct committees are responsible for the maintenance and regulation of water use from the drinking water systems. Inhabitants pay a small monthly connection fee. Upon paying the fee, virtually unlimited amounts of water can be extracted because water use is not really monitored and legal fines for misuse of water (irrigation purposes) are not imposed. This lack of institutions makes the drinking water an open access resource, rather than a commonly owned and managed property.

## Research Framework

### Assessing Water Scarcity

One thing is certain in the future as human population and food demand in the Cabuyal River watershed increase, water and land use will change, and there will be increasing pressures on water and land resources. Competition for water to meet agricultural, domestic and industrial water demands will increase. Experience with stakeholders and decision making processes in the watershed showed that it is increasingly important to provide quantitative information about the state of water resources (CIAT, 1997), and how supply and use of water change over space and time as changes in the landscape and demographic patterns occur. Local decision-makers are generally not very aware of the interdependence between different resources, the impact of using them, and any associated upstream-downstream affects within the watershed (Knapp et al., 1999). Providing this information is considered a critical part in negotiating compromises to resolve conflicts, gaining commitment of local stakeholders to institutional arrangements and resource preserving management practices, and helping decision-makers guide development in a direction that is desirable for local communities and their people.

This overall goal of this dissertation is to study the dynamics of water supply and water demand under different directions of future development in the Cabuyal River watershed. The framework for this dissertation research is based on evaluating and quantifying water scarcity for the current situation and for future scenarios. This framework is a specific implementation of what Waltner-Toews (1996) referred to as conducting a "fitness test for ecosystem health", where health refers to water availability/scarcity over space and time, and the ecosystem to a watershed. A future situation is analyzed by quantifying the effects of the drivers under that path of development and comparing the situation before and after applying the stresses. Although the focus is on the availability and use of water resources, effects of changes in land use are accounted for as well. Figure 1-5 gives an outline of the research framework and the different steps involved. Each step is explained in detail.

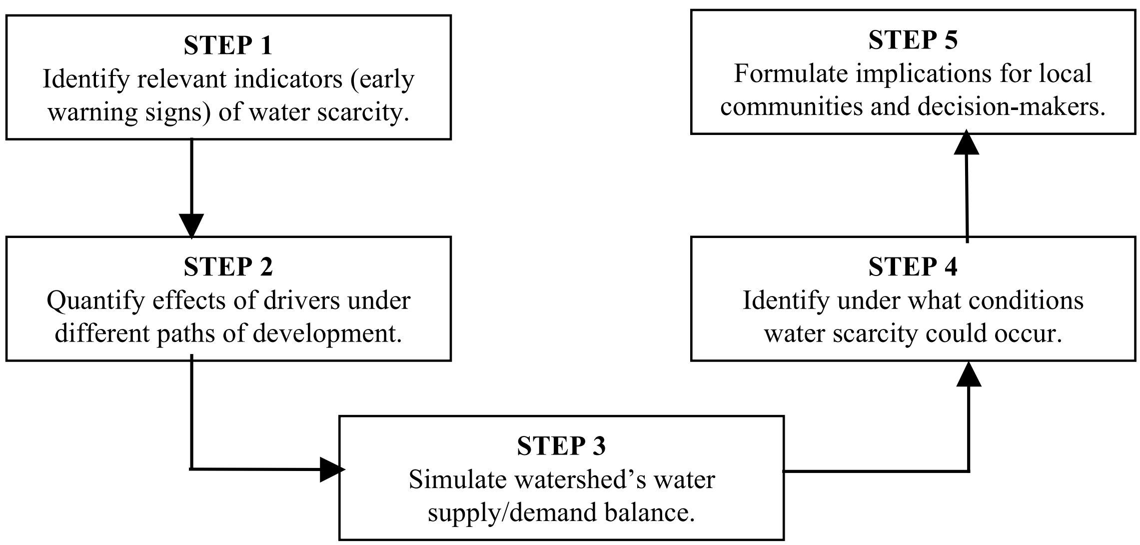



Figure 1-5. Framework and steps involved in assessing water scarcity under different paths of development at a watershed scale.

First, Relevant indicators (early warning signs) of water scarcity must be identified (Step 1). Observations in a watershed include increased crop loss due to increased drought, inability of farmers to irrigate crops, insufficient drinking water availability, lower river flow rates, an increasing number of artesian wells running dry, and growing conflict about water use. For a simulation study, one can look at the AWR throughout the year, the percentage of AWR that is used to meet domestic, industrial, and agricultural water demands, the location in the watershed where water availability is lowest compared to the water needs, and during what time of the year the risk for water scarcity is highest.

Secondly, the relevant drivers under different paths of development must be identified and their effects on the watershed quantified (Step 2). A driver is a change in the biophysical or socioeconomic environment that affects the water balance of the watershed during at least part of the year, or may result in permanent changes in water supply or water demand. Drivers that are considered in this study are land use changes, increase in population and demographic shifts within the watershed, industrial development, expansion of the area irrigated land, changes in the locations where water is extracted from streams, and the construction of dams.

Thirdly, water supply and water demand in the watershed is simulated using a watershed model (Step 3). The Spatial Water Budget Model (SWBM) was developed for this purpose. This model helps quantify watershed responses to the above mentioned drivers. It is a critical tool for assessing water scarcity over space and time on a watershed scale. Because the stream network takes a central position in the watershed—it is the medium along which effects of land use and water use accumulate—it is also the key component of SWBM.

Fourthly, simulation results are analyzed and the indicators of water scarcity are calculated (Step 4). A comparison is made between simulated water supply and water demand before and after accounting for the changes that take place in the watershed. By evaluating the effects of these changes, one can identify under what conditions the indicators could exceed critical values and, consequently, when water scarcity might occur.

Fifth, implications for local communities and policy makers can be formulated (Step 5). Information on the state of water resources under a range of conditions can improve the capacity of multi-institutional alliances like CIPASLA to perform some of the critical functions identified by Ravnborg and Ashby (1996). They can become proactive and develop appropriate rules and norms for resource use, initiate water resource conservation activities, identify better water allocation techniques, and formulate specific needs for community participation and demand for external support. Results could also help design water use monitoring schemes under a wide range of conditions and suggest specific early warning signs of water scarcity that farmers could look for.

## Outline of the Dissertation

The dissertation is organized around several distinct research activities. Each activity is described in a separate chapter. Every chapter is written in publication format, which makes it easy to read and understand it without reading the preceding chapters.

Chapter 2 explains a simplified drainage and lateral flow model, which is part of Spatial Water Budget Model (SWBM). This simplified drainage and lateral flow model approximates daily drainage out of hill slopes to streams. The model is a distributed delay model with 2 compartments that describes movement of water below the root zone to streams, without quantifying lateral flow of water along the pathways down slope.

Chapter 3 introduces the SWBM model. The model is mainly based on existing knowledge on hydrological processes and makes use of GIS raster structures. All governing equations and the implementation of the model in ArcView GIS are explained. The model was calibrated and evaluated for the Cabuyal River watershed, Colombia.

Chapter 4 gives a detailed explanation of the simulation of water use and dams by the SWBM model. Domestic, industrial and agricultural water demands in the 1990s in the Cabuyal River watershed were quantified. The implications of actual water use and hypothetical dams on water availability in the Cabuyal River watershed are analyzed.

Chapter 5 explains a stochastic model developed to generate land use patterns for any time in the future. The model accounts for the effects of various landscape characteristics that are considered relevant to describe how land use changes. Relative tendencies to move from one to another land use type are specified. The model was used to generate a plausible land use pattern for three different scenarios for the Cabuyal River watershed in 2025.

Chapter 6 discusses the implications of various paths of future development on the health of the Cabuyal River watershed in 2025 on water availability and water scarcity. Three different scenarios were developed based on contrasting but plausible views about the future economy, landscape, population, and use of water and land resources in the watershed: Corporate Farming, Ecological Watershed, and Business as Usual scenarios. Critical aspects of water availability in the Cabuyal River, current water management practices, and implications for local communities and decision-makers are discussed.

Finally, Chapter 7 summarizes the results of this study.

# CHAPTER 2
# SIMPLIFIED DRAINAGE AND LATERAL FLOW MODEL

## Introduction

Soil water above the Drained Upper Limit (DUL) water content is subject to drainage. Drainage water is also referred to as gravitational storage or detention storage (Black, 1996). Darcy's Law provides the basis for describing the movement of soil water as a result of differences in hydraulic head. The Richards Equation is the governing, continuous equation for water flow in an unsaturated soil (Richards, 1931; Swartzendruber, 1969), and when saturation prevails it becomes the Laplace equation. These equations must be solved for existing boundary conditions. In practice, finite difference or finite element methods are used to obtain a numerical solution for these equations (Wang and Anderson, 1982).

In the Spatial Water Budget Model (SWBM) it is assumed that an impervious rock layer causes the gradient in hydraulic head for lateral water flow (Figure 2-1), and that all lateral flow eventually reaches a stream. A simplified model was developed to overcome a number of difficulties in calculating lateral flow to streams in a hillside watershed that has a complex and heterogeneous landscape. First, calculation of lateral water flow requires detailed information on soil properties, geology, and presence of any confined and unconfined ground water aquifers. Such specific data are generally only available for experimental watersheds in which many detailed measurements have been taken. This generally does not apply to the typical agricultural hillside watersheds in Latin America.

Secondly, the model can be applied to any spatial scale, regardless of the level of complexity and heterogeneity of the landscape. The model works for a single hill slope with a single stream, as well as for a large watershed with multiple streams. Thirdly, implementing a finite difference method in a raster GIS requires that the GIS' programming language allows calculating the interactions among neighboring grid cells. ArcView GIS' scripting language Avenue (ESRI, 1996a) currently does not provide this capability. The simplified drainage model is computationally efficient and was fully integrated with other modules of SWBM.

This chapter explains the simplified drainage and lateral flow model . Use of this model is illustrated for a simple situation: water flow in one direction along a single hill slope with underlying bedrock. Simulated drainage rates of the simplified drainage model are presented and compared with those from a finite difference approximation of Darcy’s Law. They are also compared with those of a 1-compartment delay model to illustrate the advantage of using 2 compartments.

## Materials and Methods

### Theoretical Darcy Flow Model

Figure 2-1 shows a representation of a hill slope as a series of $N$ connected land units. Land unit $j$=1 is at the top of the hill and land unit $j$=$N$ is at the bottom of the hill, adjacent to a stream. Drainage water flows along an impervious rock layer to the lowest land unit $j$=N from where it flows into the stream.

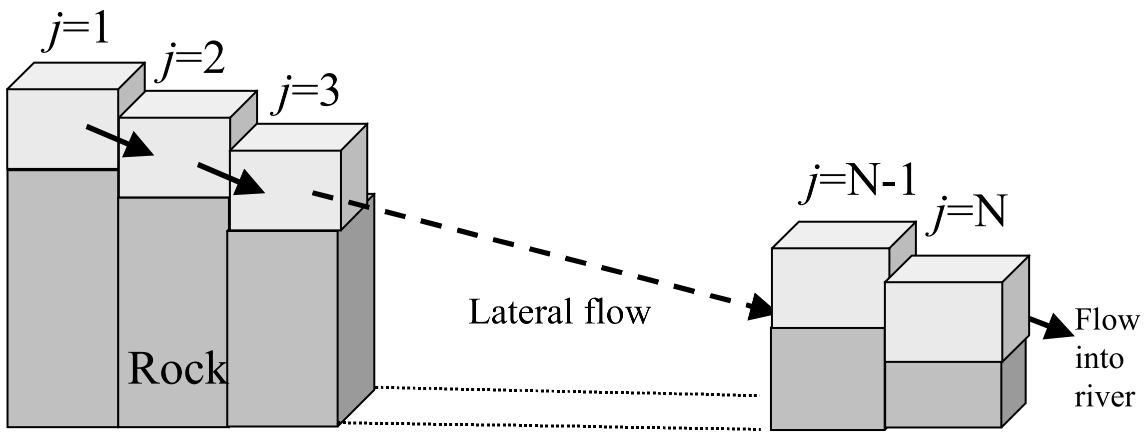



Figure 2-1. Representation of a single hill slope as a series of N connected land units (grid cells). The light colored part of the hill slope is soil that has a detention storage capacity greater than zero, the dark colored part is an impervious rock layer.

If no additional water enters the soil after t=0, then for t>0 the water content decreases until it reaches the drained upper limit in each land unit *j*, at which time drainage out of the soil profile stops. *Wj* indicates the drainable amount of water in land unit *j* ($m^3$). The change in this amount of water ($\Delta W_j$) during a time interval $\Delta t$ can be approximated by the finite difference representation of Darcy's Law:

$$\frac{\Delta W_j}{\Delta t} = K_j \cdot A_{j-1} \cdot \frac{h_{j-1} - h_j}{\Delta x} - K_j \cdot A_j \cdot \frac{h_j - h_{j+1}}{\Delta x}, \tag{2-1}$$

where $h_j$ is the average hydraulic head hydraulic in land unit *j*, measured with respect to some common datum level, $K_j$ is the hydraulic conductivity in land unit *j* (m $d^{-1}$), $\Delta x$ is the distance between the centers of two adjacent land units (m), $A_j$ is the cross-sectional area through which water flows from land unit *j* to *j*+1 ($m^2$), and $\Delta t$ is the time step (d).

On any day *t*, total drainage out of the hill slope in the stream, $TOTDRS_{1,t}$ ($m^3 d^{-1}$), is the rate of water flow out of the lowest land unit *j=N*. This volume is equal to the cumulative net change in drainable amount of water in all land units at any particular day:

$$\text{TOTDRS}_{1,t} = -\sum_{j=1}^{N} (W_{j,t-1} - W_{j=t}). \tag{2-2}$$

The relative daily drainage fraction at day $t$, $\text{RELDRN}_t$ ($d^{-1}$), is calculated as:

$$\text{RELDRN}_t = \frac{\text{TOTDRS}_{1,t}}{\sum_{j=1}^{N} W_{j,t-1}}. \tag{2-3}$$

A simulation was performed for a hill slope consisting of N=10 land units, each 50 m wide and 50 m long, a slope of 20% and a hydraulic conductivity of 1 m $d^{-1}$. The soil profile was assumed saturated at t=0 with a uniform drainable water depth of 1 m. The profile was allowed to drain for 100 days. No water was added during that period.

Figure 2-2 shows the drainage rate $\text{TOTDRS}_1$ over time. It is nearly constant at a maximum rate of 500 $m^3d^{-1}$ during the first 20 days, after which is gradually decreases. The total amount of drainable water, which is the area below the curve, is 25,000 $m^3$. Figure 2-3 shows the remaining fraction of the amount of drainable water over time, for each land unit $j$=1..10 (black curves) and for the hill slope as a whole (red curve). The water content decreased quickest in the land unit furthest away from the stream ($j$=1) and slowest in the lowest land unit adjacent to the stream ($j$=10). Figure 2-4 shows the relative drainage fraction RELDRN for the hill slope as a whole. Note that the y-axis in Figure 2-3 is identical to the x-axis is Figure 2-4. Thus, the lowest point of the curve in Figure 2-4 corresponds to $t$=0 and the highest point to $t$=100. The relative daily drainage rate was lowest when the soil profile was saturated (at $t$=0) and highest when the soil water content was near DUL (at $t$=100).

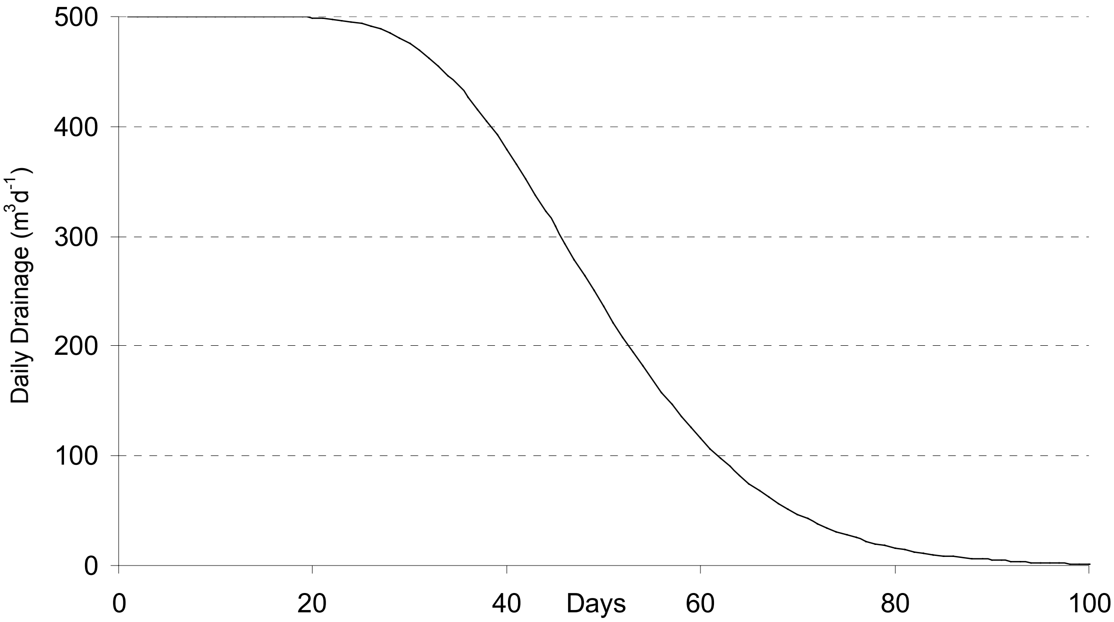



Figure 2-2. Simulated drainage out of a hill slope of 10 land units, each 50 m wide and long, calculated with a finite difference approximation of Darcy's Law, for an initial drainable water depth of 1 m, 20% slope, and hydraulic conductivity of 1 m $d^{-1}$.

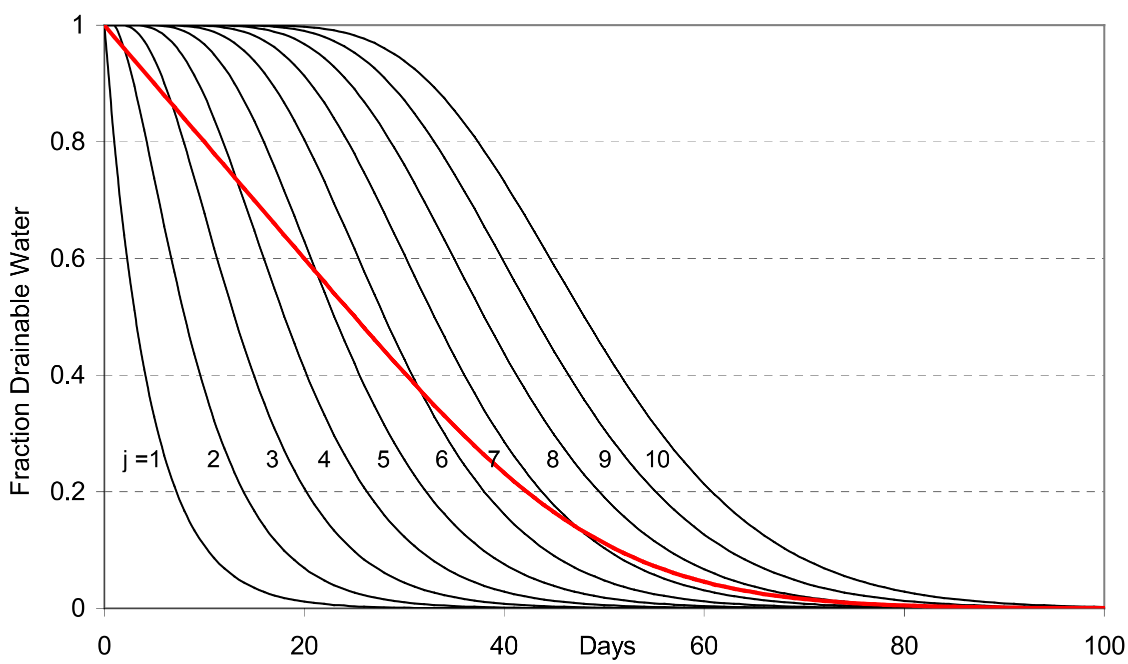



Figure 2-3. Remaining fraction of the amount of drainable water for all N=10 land units (black curves) and for the hill slope as a whole (red curve), calculated with a finite difference approximation of Darcy's Law.

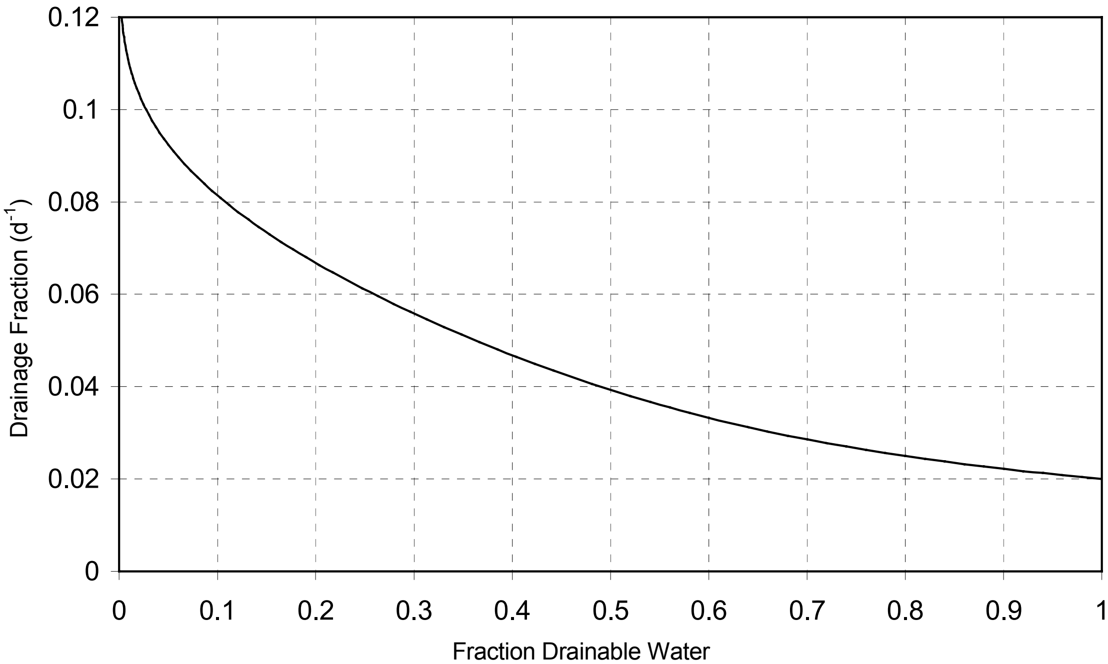



Figure 2-4. Relative daily drainage fraction as a function of fraction drainable water, for the hill slope as a whole, calculated with a finite difference approximation of Darcy's Law.

Simplified Drainage Model

An empirical approach was developed to approximate daily drainage out of a hill slope into the river ($TOTDRS_1$). This simplified drainage model is a 2-compartment, distributed delay model to describe movement of soil water to streams without computing flow between adjacent land units along the flow path. The actual water content in the soil is not estimated. The model was developed to mimic the rate of drainage indicated by the curves in Figures 3-2 and 3-4 and the red colored curve in Figure 2-3, but not those of the ten individual curves in Figure 2-3. Figure 2-5 gives a representation for the method of calculating drainage out of the soil profile to the stream.

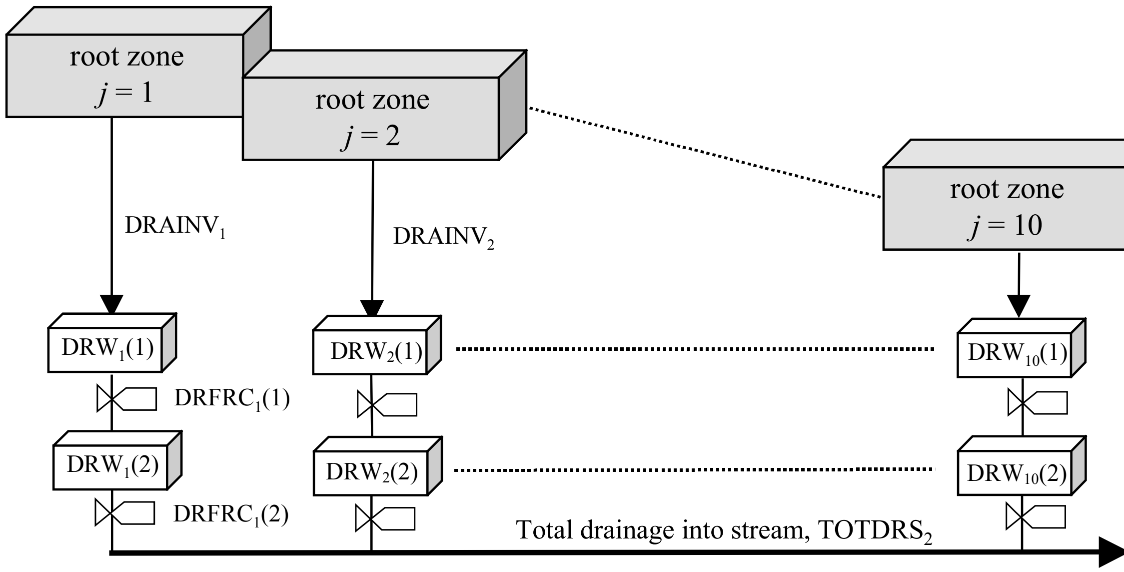



Figure 2-5. Representation of the soil profile as a series of independent land units, each having a root zone and two compartments that store water and delay its movement to streams.

$DRW_j(X)$ is the drainable soil water ($m^3$) in compartment X of land unit *j*. All compartments are assumed equal in volume. The changes in water content ($m^3d^{-1}$) in the two drainage water compartments of land unit *j* are calculated as:

$$\Delta DRW(1)_j/\Delta t = (DRAINV_j) - (DRFRC_j(1) \cdot DRW_j(1)), \tag{2-4}$$

$$\Delta DRW(2)_j/\Delta t = (DRFRC_j(1) \cdot DRW_j(1)) - (DRFRC_j(2) \cdot DRW_j(2)), \tag{2-5}$$

where $DRAINV_j$ is the daily drainage out of the root zone ($m^3d^{-1}$) and $DRFRC_j(S)$ is the daily fraction of the stored water that drains out of compartment S of land unit *j* ($d^{-1}$), with S=1 or S=2. These drainage fractions change over space and time, and are calculated in four steps.

First, for each land unit *j*, an initial drainage fraction $DRFRC_{INI,j}$ ($d^{-1}$) is determined from the average slope along the flow path of land unit *j* ($SLOPE_{AV,j}$, %), the average hydraulic conductivity along the flow path ($K_{AV,j}$, m $d^{-1}$), and a drainage water retention parameter DRWRT. This parameter is determined by model calibration.

$$\text{DRFRC}_{\text{INI,j}} = \text{DRWRT} \cdot \text{SLOPE}_{\text{AV,j}} \cdot \text{K}_{\text{AV,j}}. \tag{2-6}$$

Secondly, Figure 2-3 illustrated that the water content in a land unit decreases faster if the land unit is further away from the stream. A linear relationship between flow length to the stream and drainage rate has been assumed, as illustrated in Fig. 2-6A. For every land unit *j*, the correction factor of drainage for flow length is calculated as:

$$\text{COR}_{\text{FL}},_{\text{j}} = 1 + (\text{MX}_{\text{FL}} - 1) \cdot \frac{\text{FLOWL}_{\text{j}}}{\text{FLOWLMX}}, \tag{2-7}$$

where $\text{FLOWL}_j$ is the flow length from land unit *j* to the stream (m), FLOWLMX is the maximum length of the flow path (from hill top to stream), and $\text{MX}_{\text{FL}}$ is the maximum correction factor, which is determined by model calibration. Thus, land unit *j*=1 (at the hill top) is assumed to have a drainage factor that is $\text{MX}_{\text{FL}}$ higher than the drainage factor of land unit *j*=N (adjacent to the stream). The factors $\text{DRFRC}_{\text{INI,j}}$ and $\text{COR}_{\text{FL,j}}$ are constant over time. Therefore, Equations 2-6 and 2-7 are evaluated only once, at *t*=0.

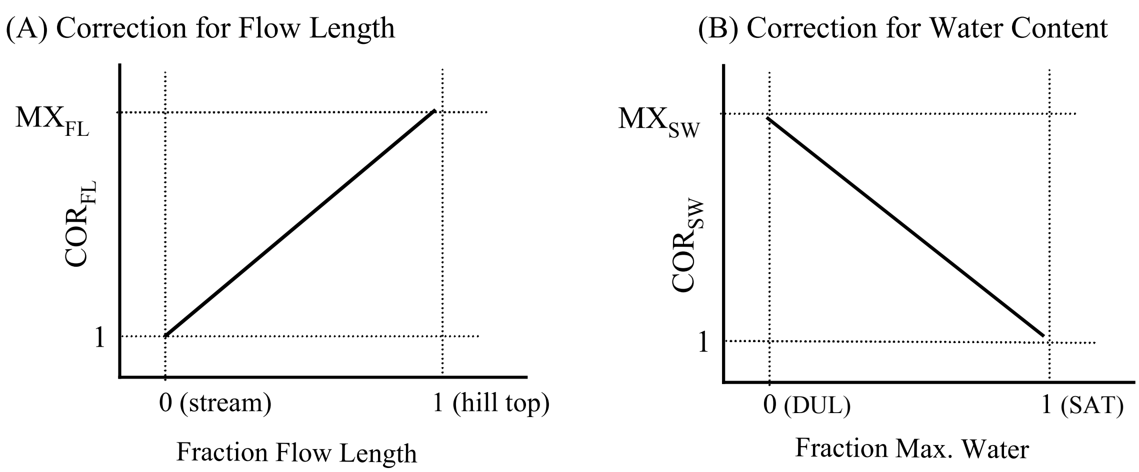



Figure 2-6. Linear relationships to correct the drainage fractions of the compartments of the distributed delay model; (A) correction for flow length; (B) correction for water content.

Thirdly, Figure 2-4 illustrated that the relative daily drainage fraction increases with decreasing water content. A linear relationship between water content and drainage rate has been assumed (Figure 2-6B). For the first and second compartments for each land unit *j*, the correction factors of drainage for water content are calculated as, respectively:

$$COR(1)_{SW,j} = MX_{sw} - (MX_{SW} - 1) \cdot \frac{DRW_j(1)}{DRWMAX}, \tag{2-8}$$

$$COR(2)_{SW,j} = MX_{SW} - (MX_{SW} - 1) \cdot \frac{DRW_j(2)}{DRWMAX}, \tag{2-9}$$

where DRWMAX the maximum amount of drainage water ($m^3$) in a compartment, which is assumed to be equal for all compartments, and $MX_{SW}$ is the maximum correction factor, which is determined by model calibration. Thus, a compartment that is near empty has a $MX_{FL}$ higher drainage fraction than a full compartment.

Fourthly, the daily drainage fractions for the first and second compartments of land unit *j*, $DRFRC_j(1)$ and $DRFRC_j(2)$, are calculated as:

$$DRFRC_j(1) = DRFRC_{INI,j} \cdot COR_{FL\,j} \cdot COR(1)_{SW\,j}, \tag{2-10}$$

$$DRFRC_j(2) = DRFRC_{INI,j} \cdot COR_{FL\,j} \cdot COR(2)_{SW\,j}. \tag{2-11}$$

The theoretical rate of drainage from the soil profile to the river is estimated by the accumulated drainage out of the second compartments of all land units, $TOTDRS_2$ ($m^3d^{-1}$):

$$TOTDRS_2 = \sum_{j=1}^{N} DRFRC_j(2) \cdot DRW_j(2). \tag{2-12}$$

Equations 2-8 through 2-12 have to be calculated for each land unit on a daily basis.

Overview of Analysis

First, the simplified drainage model was calibrated for the simple hill slope problem by adjusting the three parameters P, $MX_{SW}$ and $MX_{FL}$ to obtain the best fit between the drainage rates $TOTDRS_1$ (Eq. 2-2) and $TOTDRS_2$ (Eq. 2-12). The criterion for best fit was minimum Mean Square Error (MSE), based on a 100 day simulation period. The 3-parameter optimization was reduced to a 2-parameter optimization because for each $MX_{FL}$ value there was only one DRWRT value for which $TOTDRS_1$ and $TOTDRS_2$ are identical at t=0 (i.e. both curves have the same intersect with the y-axis). Five plausible values of the correction factor $MX_{FL}$ were considered: 1.00, 1.25, 1.50, 1.75 and 2.00. Each of these values was varied in combinations with values of the correction factor $MX_{SW}$ ranging from 2.1 to 2.8, in increments of 0.1. The maximum flow length, MXFLOWL, was 500 m. The maximum amount of water in each compartment, DRWMAX, was 1,250 $m^3$, equivalent to a drainable water depth of 1 m in a 50 x 50 m land unit. At *t*=0, the water content in root zone was assumed at DUL and storage in each compartment was set to its maximum, DRWMAX.

Secondly, simulated drainage rates of the 2-compartment distributed delay model were compared to those of a similar 1-compartment model. The maximum storage capacity of a compartment in the single compartment model was doubled so that the same volume of water could be held (1 m drainable water depth). Moreover, both variable and constant drainage factors were applied to each model to illustrate the effects of drainage factors that vary over time and space. The drainage factors $DRFRC_j(S)$ could be kept constant by simply setting $MX_{FL}$=1 and $MX_{SW}$=1 (see Equations 2-7, 2-8 and 2-9).

The simulations and model calibration were performed with a simple program written in Fortran Simulation Translator (Rappoldt and Van Kraalingen, 1996).

## Results and Discussion

### Calibration of the 2-Compartment Model

Table 2-1 gives the Mean Square Error of the fit between $TOTDRS_1$ and $TOTDRS_2$. A lowest MSE of 51 was obtained for $MX_{FL}$ =1.0, $MX_{SW}$=2.24 and DRWRT= 0.002. For this set of parameters, curve B in Figure 2-7 shows the corresponding simulated drainage rate. Curve A shows the simulated drainage for the theoretical Darcy Flow model. The fit between both curves is very good. The lowest MSE was obtained when no correction for flow length was used. The correction for flow length is thus redundant for this simple problem. The minimum MSE would increase if any correction in flow length (i.e. $MX_{FL}$ > 1.0) is used.

Table 2-1. Mean of square errors (MSE) of the drainage rates of the theoretical Darcy model and the drainage rates of the simplified, 2-compartment distributed delay drainage model, for different values of parameters DRWRT, $MX_{SW}$, and $MX_{FL}$.

| | | $MX_{SW}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $MX_{FL}$ | DRWRT | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 |
| 1.00 | $2.000 \cdot 10^{-3}$ | 117 | 58 | 63 | 126 | 243 | 410 | 622 | 879 |
| 1.25 | $1.778 \cdot 10^{-3}$ | 158 | 84 | 69 | 109 | 199 | 334 | 511 | 726 |
| 1.50 | $1.600 \cdot 10^{-3}$ | 272 | 167 | 115 | 112 | 152 | 228 | 337 | 475 |
| 1.75 | $1.455 \cdot 10^{-3}$ | 447 | 315 | 229 | 185 | 177 | 199 | 246 | 313 |
| 2.00 | $1.333 \cdot 10^{-3}$ | 670 | 517 | 407 | 333 | 290 | 272 | 273 | 289 |

### Comparison Between 1 and 2 Compartment Models

Table 2-2 shows the optimal parameter values for which MSE was minimal. The much higher MSE value for the 1-compartment model indicates that the 2-compartment model was considerably better. This is also obvious from Figure 2-7, which shows that curves A and B are much closer than curves A and C. Figure 2-7 also shows that the distributed delay models with the variable drainage factors (curves B and C) are better than distributed delay models with constant drainage factors (curves D and E).

Figure 2-8 shows the corresponding effective daily drainage fraction for the soil profile as a function of the remaining fraction drainable water. Again, the drainage curve of the 2-compartment distributed delay model fit closest to the curve for the Darcy Flow Model.

Table 2-2. Parameter values and minimum Mean Square Error between drainage simulated with the distributed delay model and the Darcy model, for a 100 day period.

| Model | DRWRF | $MX_{FL}$ | $MX_{SW}$ | Minimum MSE |
|---|---|---|---|---|
| 1 compartment distributed delay | 0.001 | 1.0 | 2.81 | 1433 |
| 2 compartment distributed delay | 0.002 | 1.0 | 2.24 | 51 |

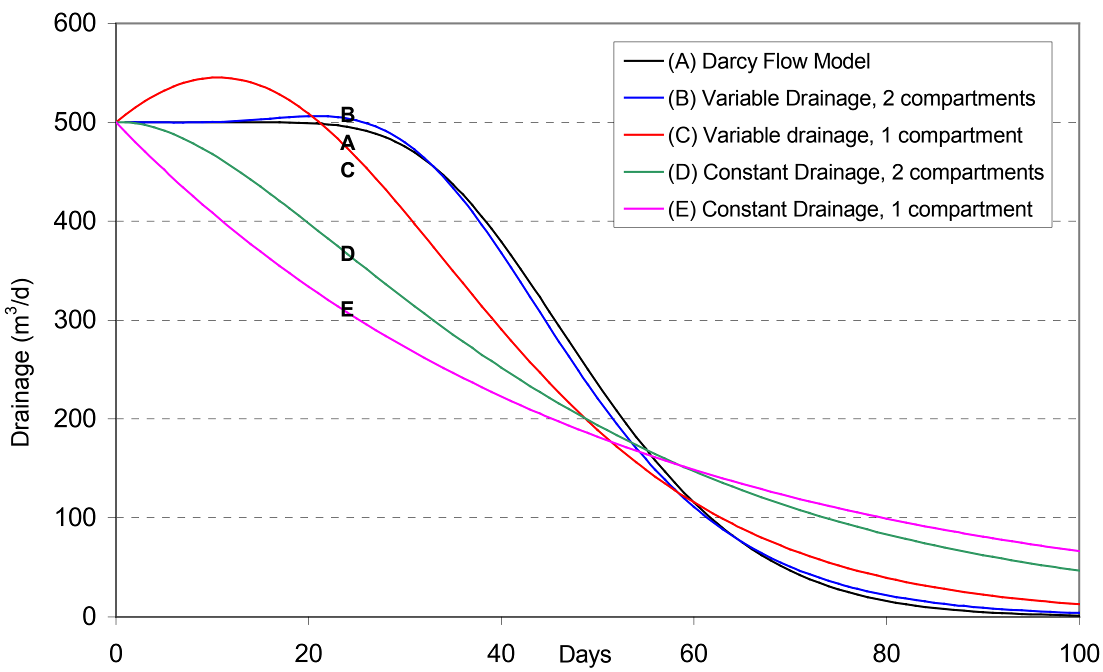



Figure 2-7. Simulated drainage out of the hill slope for the Darcy Flow model and the 1 and 2 compartment distributed delay models, with constant and variable drainage fractions.

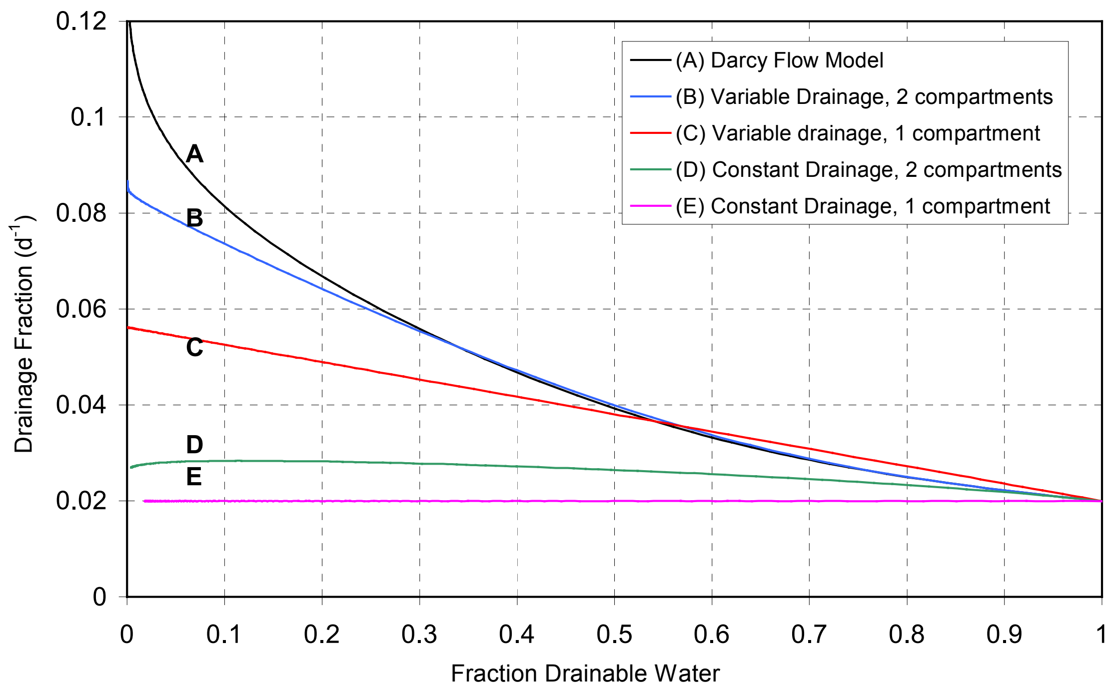



Figure 2-8. Daily drainage fraction as a function of remaining fraction drainable water, for the hill slope as a whole, for the Darcy Flow model and the 1 and 2 compartment distributed delay models, with constant and variable drainage fractions.

A distributed delay model with 3 compartments was also simulated (results not shown). The minimum MSE decreased to 4.0. However, a larger number of compartments have the disadvantage that they introduce an unreasonably long delay between the time water is added to the profile (precipitation) and drainage.

## Conclusions

The simplified drainage and lateral flow model provided an efficient way of calculating drainage out of a single hill slope. For the simple case study problem, the model was easily calibrated against drainage calculated with a theoretical Darcy model, requiring only data on hydraulic conductivity and slope. The model gave estimates of drainage out of a hill slope that were very close to those approximated with the theoretical Darcy model. This was possible by applying daily drainage fractions that varied over time. The drainage fractions changed over time because they were depended on the amount of water in the compartments. The 2-compartment distributed delay model with variable drainage fractions was considered the best for this application. It gave significantly better drainage estimates than a single compartment model.

CHAPTER 3
DEVELOPMENT AND EVALUATION OF A GIS-BASED, WATERSHED-SCALE WATER BALANCE MODEL

## Introduction

In the Cabuyal River watershed in southwest Colombia, streams are the primary source of water to serve domestic, industrial and agricultural water needs. Some families use private wells as a source of drinking water during the dry season, but water use from wells is negligible compared to water use from streams (de Fraiture et al., 1997). The flow rate in the Cabuyal River is relatively low and varies significantly over space and time. The average annual flow rate is 1000 L/s (at the watershed outlet), but it can easily double after strong rains, whereas it decreases to 250-300 L/s during the dry season (de Fraiture et al., 1997).

Local stakeholders in the watershed identified the decrease of the production capacity of water as one of the key problems in their watershed (CIAT, 1993). In general, people are very concerned about the negative effects of decreasing water yields and unregulated water extraction on water availability (de Fraiture et al., 1997). Reduced or insufficient water availability during the dry season was recognized as a serious problem. Competition for water and conflicts between and within communities about water use has increased during the last decades (Ravnborg and Ashby, 1996). Local stakeholders are concerned about the negative effects of land use changes (in particular deforestation) and lack of adequate soil conservation techniques on the hydrological response of the watershed. They argue that river flow rates have generally become less predictable and that higher peak flows rates occur.

Most water problems occur in the middle and lower part of the watershed. Although downstream communities have the advantage of benefiting from a larger catchment area and thus higher stream flows, they also experience the greatest effects of any changes in land and water use that occur at higher elevations. Downstream communities argue that deforestation in the higher part of the watershed has resulted in generally lower river flows in the lower part of the watershed, and that they have little water available for irrigation because communities in the middle and upper part of the watershed extract too much water.

One thing is certain as human population and food demand in the watershed increase in the future, water and land use will change, and there will be increasing pressures on water and land resources. Competition for water to meet agricultural, domestic and industrial water demands will increase. Experience with decision-making processes in the watershed showed that it is increasingly important to provide quantitative information about the state of water resources, and how demand and supply of water resources could change over space and time as a result of changes in land use, population growth and demographic shifts within the watershed, industrial development and construction of dams. Local stakeholders are not very aware of the interdependencies between land and water resources, the impact of using them, and any upstream-downstream effects. Providing this information is considered a critical part in negotiating compromises to resolve conflicts, gaining commitment of local stakeholders to institutional arrangements and resource preserving management practices, and helping decision-makers guide development in a direction that is desirable for local communities and their people (Knapp et al., 1999).

The Spatial Water Budget Model (SWBM) has been developed to assist in this task. SWBM is based on existing knowledge of hydrological processes and requires relatively few data. This model is a tool for analyzing temporal and spatial variation in the overall water balance and in stream water availability at a watershed scale as a result of temporal and spatial changes in climate, land use, water demand, different water extraction regimes, and in the daily operation of dams. The model is strong in that the stream network takes a central position. This allows examining the spatial and temporal variability of availability and fate of stream water, rather than detailing the movement of soil water. This chapter provides technical details on SWBM and gives all governing equations. The model was calibrated and evaluated for the Cabuyal River watershed. This chapter focuses on the simulation of the hydrological response of a watershed landscape, and how the potential availability of water in streams changes over space and time. Simulation of water use and the operation of dams are discussed in Chapter 4.

## Background and Literature Review on Hydrologic Modeling

### Hydrological Analysis and Modeling

Hydrologic analysis and hydrological modeling deal with issues in three rather distinct areas (Maidment, 1993). The first area is concerned with *pollution control* and mitigation. The fate of nutrients and pesticides in both groundwater and surface water is of central concern. The second area involves *flood control* and mitigation, which includes storm runoff and storm drainage control, flood prediction and flood plain management. The third area deals with *water utilization*, i.e. the supply and allocation of a limited amount of water among competing demands in the domestic, agricultural and industrial sectors, as environmental and natural systems. Numerous hydrological models have been developed during the last decade. These models can generally be grouped into surface water hydrology models, surface water quality models, groundwater flow models and groundwater constituent transport models (Maidment, 1993).

A simulation model that is used for analyzing temporal and spatial variation in the water balance of hillside watersheds should meet five major requirements. First, the model should be a continuous simulation, distributed parameter, and watershed-scale model. Secondly, the model must properly work for steep topography of hillside watersheds in Latin America and the Caribbean. Thirdly, the strength of the model must be in estimating water availability in the streams and calculating a watershed water balance, rather than performing comprehensive analyses of water and nutrient flows in multiple soil layers. Fourthly, simulation of dams must be possible. Dams have been recognized as essential in water management in many regions in the next century (Seckler et al., 1998; Serageldin, 1998). And lastly, the model should have relatively low data requirements because there are generally few data available for the agricultural hillside watersheds in Latin America and the Caribbean.

Various existing watershed-scale models have been considered for the proposed watershed analysis. These models are the Annualized Agricultural Non-Point Source Pollution Model (AnnAGNPS) (Bosch et al., 1998), the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS 2000) (Dillaha et al., 1998), the Simulator for Water Resources in Rural Basins (SWRRB) (Arnold et al., 1990), the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1995), the Better Assessment Science Integrating Point and Nonpoint Sources model (BASINS) (Lahlou et al., 1998), and the Object Watershed Link System (OWLS) (Shen and Beschta, 1999). These models did not meet all the requirements. In general, they were too complex, too data demanding, or incapable to simulate and manipulate stream flows and simulate dams. I have therefore developed SWBM.

Combining Hydrological Models with GIS

Geographic Information Systems (GIS) can link remote sensed data on land use/land cover, soils, weather and hydrology to topographic data and to other information concerning processes and properties related to geographic location (DeVantier and Feldman, 1993). GIS has emerged as an extremely effective tool for analyzing and prioritizing natural resource management alternatives. For numerous agricultural and environmental research and planning purposes, environmental models are increasingly being used in combination with GIS. Applications of GIS and environmental modeling include, but are not limited to, land resource assessment and landscape planning (Burrough, 1986), water quality and nutrient management planning (Fraisse et al., 1994; Negahban et al., 1996), land cover/land use change analysis, crop growth modeling (Engel et al., 1997; Papajorgji et al., 1994) and the identification of critical areas of point and nonpoint source pollution in agricultural watersheds (Srinivasan and Engel, 1994).

Models can be combined with a GIS through a loose coupling, a tight coupling, or an internal coupling (embedded modeling) (Goodchild, 1993). Loose and tight couplings are most common. The GIS usually performs functions that can be characterized as preprocessing and post-processing. One of the major impediments to such linkage lies in the lack of common data models, structures and common interfaces. Nevertheless, this approach has proven to be quite successful over the last two decades, particularly for distributed parameter models that are generally very data intensive. The GIS software most often used is the Geographic Resources Analysis Support System (GRASS) (U.S. Army Corps of Engineers, 1991) and ARC/INFO (ESRI, 1997a). Examples of hydrological models that have been coupled to GRASS include ANSWERS (Rewerts and Engel, 1991) and SWAT (Srinivasan and Arnold, 1994). Cronshey et al. (1996) describe a prototype for a generic GIS water-quality model interface that links AGNPS, SWRRB, EPIC and GLEAMS to GRASS. ARC/INFO has been linked to, among others, the ANSWERS (Batchelor et al., 1994) and AGNPS models (Hayes and Zhang, 1998). There are also various freely or commercially available comprehensive watershed modeling packages that include hydrological models and a GIS interface. For example, the Watershed Modeling System (Environmental Modeling Systems Incorporated, http://www.ems-i.com/) includes the HEC-1, TR-20, NFF, and Rational Method models and has an extension that links the system to ArcView GIS.

Characteristic of all these GIS-model linkages and watershed software is that the GIS is solely used for capturing, preparation, storage, retrieval and presentation of spatially variable data (i.e. preprocessing and post-processing). The question raises as to why comprehensive hydrological analysis have been performed by coupling an external model to the GIS, rather than by making use of the intrinsic modeling capabilities of GIS. Maidment (1996) noted that one of the reasons is related to the way simulation results are stored. It is common for GIS computations to be very disk dependent because the results for each computational step are written to the disk before the next step is initiated. This is a slow process and requires much disk space. From the GIS perspective there is an increasing demand for tools that perform functions other than organization and display of spatial data (Maidment, 1996). Traditionally, abstract models used for environmental simulation are quite different from those used in GIS. They use the language of mathematics and are normally implemented in general high-level programming language rather than the language of GIS functions and spatial data structures. The idea that GIS might be a tool to support sophisticated spatial-temporal modeling is still far from being accepted.

GIS software and technology has enormously improved during the last years. The syntax of ArcView GIS's scripting language Avenue (ESRI, 1996a) allows one to adequately embed a mathematical model and perform sophisticated spatial, hydrological and statistical analysis. This may also be possible using other GIS software. Appendix A gives an overview of the main advantages and disadvantages of GIS-embedded modeling. Specific hydrological modeling tools available in GIS include the calculation of flow direction and flow accumulation, sub-watershed delineation, stream network delineation, calculation of contributing areas, and calculation of Darcy flow fields (ESRI, 1994, 1996b; Warwick and Hanness, 1994). The first four types of calculations are very fundamental to GIS-based hydrological analyses and are explained in detail in Appendix B.

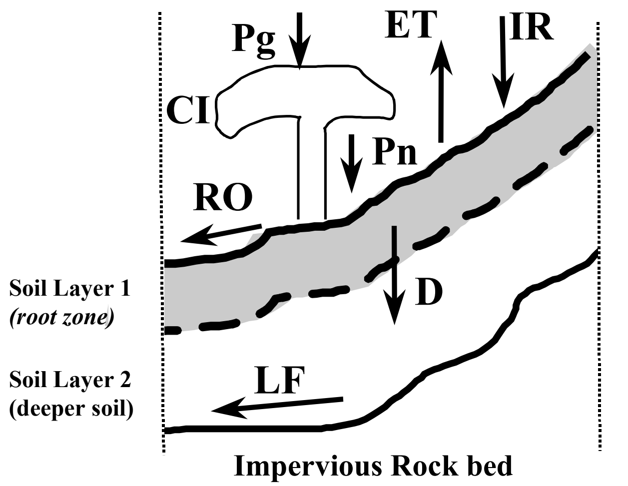
Still, the number of applications that truly make use of GIS-intrinsic modeling capabilities is small. Raper and Livingstone (1996) and DeVantier and Feldman (1993) discuss some early applications of embedded hydrological modeling. Most GIS-embedded models are relatively simple models that are used for static rather than dynamic analysis. Examples of static models are the calculation of spatial distribution of surface and soil water, soil erosion potential (Moore et al., 1996), and spatially-variable leaching potentials (Tim, 1996). Watkins et al. (1996) evaluated simple dynamic models that simulate ground water flow patterns and contaminant dispersion by performing a sequence of map algebra calculations for changes in flow pattern and hydraulic head.

## Description of the Watershed Model

The Spatial Water Budget Model (SWBM) is a continuous simulation, distributed parameter, watershed scale model that simulates water supply and demand over space and time on a daily basis using raster GIS data structures. The five major processes that are simulated by the model are: (a) land unit water balance, (b) water flow to streams, (c) stream water flow balance, (d) water storage in dams, and (e) water extraction from dams and streams for domestic, agricultural and industrial uses. The model was designed for analyzing temporal and spatial variation in the overall water balance, stream water flow rates and water availability on a daily basis at a watershed scale. The model has been particularly designed for application in hillside watersheds in Latin America and the Caribbean, but can be applied to other watersheds as well. The model does not simulate storm peak flow, sediment loading, soil erosion or vegetation growth/yield. This section describes the land unit water balance, water flow to streams, and the stream water flow balance of SWBM. Water extraction and water storage in dams are part of the stream water balance, but they are explained in more detail in Chapter 4. Appendix C gives a listing of all model variables and their units.

## Land Unit Water Balance

The water balance for each land unit $j$ is a based on the soil water balance implemented in the DSSAT crop growth models (Ritchie, 1998). Figure 3-1 gives a schematic representation of the soil profile and indicates the major processes. The root zone is the soil layer from which evapotranspiration water loss occurs. The maximal vegetation rooting depth determines the depth of this layer. The lower boundary of the soil profile is assumed to be an impervious (rock) layer that is parallel to the soil surface. Soils are assumed sufficiently deep so that the impervious layer is always below the rooting depth. Between the impervious layer and the root zone is the deeper soil water layer. The impervious layer is assumed to create the gradient in hydraulic head for lateral water flow in the deeper soil layer.




Processes:

$P_g$ = gross precipitation

$P_n$ = net precipitation

ET = evapotranspiration

IR = irrigation

RO = surface runoff

D = vertical drainage

LF = lateral flow

CI = canopy interception

Figure 3-1. Schematic representation of the soil profile for a single land unit.

For any land unit *j,* the change in volumetric soil water content in the root zone is:

$$\Delta SW_j/\Delta t = (P_{N,j} + IR_j - CI_j - AET_j - RO_j - D_j) / DLAYR_j, \tag{3-1}$$

where $SW_j$ is the volumetric soil water content in the root zone in $m^3m^{-3}$, $P_{N,j}$ is net precipitation, $IR_j$ is applied irrigation; $CI_j$ is canopy intercepted rainfall; $AET_j$ is actual evapotranspiration; ROj is surface runoff; $D_{j,}$ is water drainage to the deeper soil layer, and $DLAYR_j$ is the thickness of soil root zone (in mm). The unit of all water amounts at the right hand side of Eq. 3-1 is mm (water depth) $d^{-1}$. Each of the relevant processes is explained in subsequent sections.

<u>Evapotranspiration</u>

The evapotranspiration (ET) module of the watershed model is quite comprehensive. The daily rate of ET depends on radiation, minimum and maximum temperatures, stage of plant development, soil water status and canopy wetness. ET is calculated in four steps.

First, reference evapotranspiration for land unit *j*, $RET_j$ (mm $d^{-1}$), is calculated using the Ritchie (1972) implementation of the Priestley-Taylor (1972) equation. This method requires only daily minimum and maximum temperature and daily total radiation. Reference

ET is calculated for a canopy with a leaf area index (LAI) of 3.0 and bare soil reflection coefficient (albedo) of 0.1. Because elevation can vary significantly throughout a hillside watershed, average daily temperatures are adjusted by using an adiabatic lapse rate of 6°C per 1000 m increase in elevation (relative to the elevation of the weather station). No adjustment has been made for possible spatial variability in irradiation caused by difference in solar azimuth and zenith angles, or for spatial variability in rainfall due to orographic effects.

Secondly, crop coefficients are used to represent the ability of land cover type to reach reference ET. Doorenbos and Pruitt (1977) introduced the concept of crop coefficients to relate actual crop evapotranspiration to a reference evapotranspiration and the crop development stage. Maximum ET of the actual land cover, $MET_j$ (in mm $d^{-1}$) is:

$$MET_j = CF_j \cdot RET_j, \tag{3-2}$$

where $CF_j$ is the crop coefficient. It would actually be more appropriate to refer to $CF_j$ as *land use/land cover* rather than *crop* coefficient because itcan be applied to land use types other than crops. However, the term crop coefficient will be used in this chapter.

Table 3-1 gives crop coefficients on a monthly basis for different land use types. The first ten land use types (No vegetation to Annual crops) are based on a classification of a 1989 Landsat Thematic Mapper image of the Cabuyal River watershed (Langford and Bell, 1997). The other four land use classes (Spring, Summer, Fall and Winter crops) were added because they are considered important for later analysis. Some crop coefficients in Table 3-1 are subjective estimates representing “average values over the watershed”. For example, different crops are cultivated in the Cabuyal River watershed, including beans, corn, cassava and a variety of vegetable crops. Different crop coefficients and a different timing and length of the growing season characterize each crop. The land use classification available for the Cabuyal River watershed only distinguishes a single class, *annual crops*. The constant value of 0.8 for *annual crops* is assumed to represent the mixture of crops that are in different development stages at any point in time.

Table 3-1. Monthly crop coefficients for the land use types in the Cabuyal River watershed.

| | Land use | Jan | Feb | Mar | Apr | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | No Vegetation | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 2 | Exposed Soil | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 3 | Scant Pasture | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| 4 | Dense pasture | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 5 | Bush Scrub | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| 6 | Young Woodland | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 7 | Mature Woodland | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 8 | Bamboo Stand | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| 9 | Coffee Plantation | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| 10 | Annual crops | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| 11 | Spring crops | 0.4 | 0.8 | 1.1 | 1.0 | 0.8 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 12 | Summer crops | 0.2 | 0.2 | 0.2 | 0.4 | 0.8 | 1.1 | 1.0 | 0.8 | 0.2 | 0.2 | 0.2 |
| 13 | Fall Crops | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.8 | 1.1 | 1.0 | 0.8 |
| 14 | Winter crops | 1.1 | 1.0 | 0.8 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.8 |

Thirdly, if the canopy is wet, canopy interception storage will first be depleted to meet evaporative demands. Canopy storage is generally evaporated at rates higher than the maximum evapotranspiration because of advection (Calder, 1982) and low aerodynamic resistance of wet canopies (Rutter, 1967). The literature provides a range of values of the rates by which wet canopy evapotranspiration exceeds the potential rate (Schulze and George, 1987). Values range from usually 1.5-2.0 to over 3 for certain forest types (Holmes and Wronski, 1981; Calder 1982). Accurate information on the type and age of the forest would be required to use the reported data. Since these are not generally available for forest in a larger watershed, a conservative and fixed value of 1.3 was used. This value was applied to all land use types classified as any kind of forest. These are *Mature Woodland*, *Young Woodland* and *Bamboo Stand* in Table 3-1. No adjustment for wet canopy ET has been made for non-forest land cover types.

Canopy interception storage, $CI_j$, may be insufficient to meet a full day's evapotranspiration demand. The daily fraction of wet canopy evapotranspiration ($FRWC_j$) is calculated and canopy interception storage is adjusted for the water lost through wet canopy ET:

$$FRWC_j = \mathrm{Min}\,(1, CI_j/(MET_j), \text{ and} \quad (3\text{-}3)$$

$$CI_j = CI_j - (FRWC_j \cdot MET_j). \quad (3\text{-}4)$$

When all water stored in the canopy has evaporated, the water needed for further evapotranspiration during the remainder of the day is taken from the soil. To determine how much water can be extracted from the soil, $MET_j$ must be corrected for actual soil water conditions. Extraction of soil water for evapotranspiration by a dry canopy is assumed zero if the soil moisture content is at or below wilting point. Possible upward movement of water from below the root zone to meet evapotranspiration demands is not considered. Uptake of soil water is not limited if the soil moisture content in the root zone is at or above some critical value, $CRIT_j$, which lies between field capacity ($FC_j$) and wilting point ($WP_j$). A depletion fraction, CFSW, between 0 and 1 is used to compute the value of $CRIT_j$:

$$CRIT_j = CFSW \cdot FC_j + (1 - CFSW) \cdot WP_j. \quad (3\text{-}5)$$

CFSW has been set to 0.6 for all land cover types, except for *No Vegetation* and *Exposed Soil* (see Table 3-11). If the soil moisture content is between the wilting point and the critical value, water extraction from the soil for evapotranspiration needs, $SET_j$ (in mm $d^{-1}$), is given by:

$$SET_j = MET_j \cdot (SW_j – WP_j) / (CRIT_j - WP_j). \tag{3-6}$$

Total actual daily evapotranspiration, $ET_j$ (mm $d^{-1}$), is then

$$ET_j = (FRWC_j \cdot 1.3 \cdot MET_j) + (1 - FRWC_j) \cdot SET_j \qquad \text{if forest land cover, and}$$

$$ET_j = (FRWC_j \cdot MET_j) + (1 - FRWC_j) \cdot SET_j. \qquad \text{no forest land cover.} \tag{3-7}$$

<u>Canopy interception</u>

Canopy interception is the interruption of the downward movement of rain and its re-distribution by the plant canopy (Black, 1996). Forest and other dense plant canopies can intercept significant amounts of rainfall, which affects evapotranspiration rates and runoff volume (Bosch and Hewlett, 1982; Schulze and George, 1987). Gash (1979) developed an analytical model to estimate forest interception. Bruijnzeel and Wiersum (1987) obtained good interception estimates with a simpler version of Gash's model. Based on that simple model, a linear regression model, the following generic equation has been used to quantify canopy interception (CI) for a land unit *j* with a specific type of land cover:

$$CI_j = Min\,(P_{G,j}, A_j + B_j P_{G,j}), \text{ with} \tag{3-8}$$

$$A_j = A_{ref} \cdot CF_j \quad \text{and} \qquad B_j = B_{ref} \cdot CF_j,$$

where $CI_j$ is intercepted rainfall (mm $d^{-1}$), $P_{G,j}$ is today's gross precipitation (mm $d^{-1}$) plus any canopy interception storage remaining from the previous day, $CF_j$ is the crop coefficient and $A_{ref}$ and $B_{ref}$ are reference canopy interception parameters for the prevailing land cover for CF=1. The difference between gross precipitation and canopy interception is referred to as net precipitation ($P_N$), the amount that reaches the soil surface.

Parameters $A_{ref}$ and $B_{ref}$ represent the canopy's ability to intercept water. This depends on canopy characteristics such as thickness, shape, and orientation of leaves. Parameter $A_{ref}$ is equal to or greater than zero, and represents the necessity for some gross precipitation to occur before throughfall commences. Parameter $B_{ref}$ is the fraction of rainfall that can still be intercepted after throughfall has started. Table 3-2 gives conservative estimates of both parameters for the ten land use types of the land use classification for the Cabuyal River watershed. The parameter values apply to a healthy and dense canopy with a crop coefficient of 1 and must be multiplied with the actual crop coefficient to obtain the actual canopy interception parameter $A_j$ and $B_j$ for the prevailing land cover in a specific month.

Table 3-2. Canopy interception parameters ($A_{ref}$ and $B_{ref}$) for different land cover types.

| Land Cover | $A_{ref}$ [mm] | $B_{ref}$ [-] | Land Cover | $A_{ref}$ [mm] | $B_{ref}$ [-] |
|---|---|---|---|---|---|
| No Vegetation | 0.00 | 0.00 | Young Woodland | 2.00 | 0.02 |
| Exposed Soil | 0.00 | 0.00 | Mature Woodland | 3.00 | 0.02 |
| Scant Pasture | 0.00 | 0.00 | Bamboo Stand | 2.00 | 0.02 |
| Dense pasture | 1.00 | 0.01 | Coffee Plantation | 1.00 | 0.02 |
| Bush Scrub | 1.00 | 0.02 | Cropped Land | 0.00 | 0.00 |

Sources: Black (1996), Bosch and Hewlett (1982) and Schulze and George (1987).

Surface runoff

Surface runoff is calculated on a land unit basis with the SCS curve number method (USDA-SCS, 1972). The curve number method was originally designed to estimate the amount of storm runoff from small rural watersheds under varying land use and soil types. The method was based on many years of studies of rainfall-runoff relationships of small watersheds in the United States. Because of its simplicity, however, the curve number method has frequently been applied to hydrologic problems for which it was not originally intended (Rallison and Miller, 1982). Heatwole et al. (1987) used a modification to the curve number method to account for antecedent soil moisture conditions. The adjustment has been adopted in SWBM. Assuming that the soil is equally moist throughout the root zone and that infiltration water can be redistributed throughout the root zone on the day of a rainfall event, then the volume of surface runoff originating from land unit *j*, $RO_j$ (in mm $d^{-1}$), is given by

$$RO_j = (P_{N,j} - 0.2 \cdot S_j)^2 / (P_{N,j} + 0.8 \cdot S_j) \qquad \text{for} \quad P_{N,j} > 0.2 \cdot S_j \tag{3-9}$$

with

$$S_j = (25400 / CN_j) - 254) \cdot (SAT_j - SW_j) / (SAT_j - WP_j), \tag{3-10}$$

where $S_j$ is the watershed storage parameter (mm), $CN_j$ is the SCS curve number for antecedent moisture conditions I (i.e. a relatively dry soil), $SW_j$, $SAT_j$ and $WP_j$ are the actual water content, water content at field saturation and water content at wilting point ($m^3m^{-3}$), respectively, and $P_{N,j}$ is daily amount of net precipitation (mm).

The curve number is a function of land use/land cover type, hydrologic condition, hydrologic soil group, and antecedent moisture conditions (AMC). Antecedent moisture conditions are indicated by I (dry conditions), II (average conditions; soil near field capacity) and III (wet conditions; soil near saturation) (USDA-SCS, 1972). CN for AMC-II is most commonly used and referred to in scientific and engineering literature. The National Engineering Handbook (USDA-SCS, 1972) provides a table to convert curve numbers for the three different AMC. The following relationships has been fitted through the curve numbers for AMC I and II in this table:

$$CN_I = (-75 \cdot CN_{II}) / (-175 + CN_{II}). \tag{3-11}$$

Partial infiltration of surface runoff in its flow path is assumed negligible and all surface runoff is assumed to reach a stream and ultimately reach the watershed outlet (but not necessarily within one day). This assumption makes the model unsuitable for storm hydrograph analysis. Surface run-on from neighboring regions is not considered.

Water content in soil root zone

The next downward flux of water into the soil root zone, $FLUX_j$ (mm $d^{-1}$), is determined from net precipitation, irrigation, surface runoff and soil water loss for ET.

$$FLUX_j = P_{N,j} + IR_j - RO_j - (1\text{-}FRWC_j) \cdot SET_j. \tag{3-12}$$

The amount of water that the root zone can hold before drainage occurs, $HOLD_j$ (mm), is calculated from yesterday's water content, $SW_j$ ($m^3m^{-3}$), the water content at saturation, $SAT_j$ ($m^3m^{-3}$), and the thickness of the root zone, $DLAYR_j$ (mm):

$$HOLD_j = (SAT_j - SW_j) \bullet DLAYR_j. \tag{3-13}$$

Case 1. If $FLUX_j$ is less than or equal to $HOLD_j$, an updated value of the soil water content $SW_j$ prior to drainage is calculated as:

$$SW_j = SW_j + FLUX_j / DLAYR_j. \tag{3-14}$$

No drainage occurs if this $SW_j$ is less than the drained upper limit of soil layer, $DUL_j$. Otherwise drainage, $DRAIN_j$ (mm $d^{-1}$), is calculated from $SW_j$, $DUL_j$, $DLAYR_j$ and the whole root zone drainage factor, RZDRF:

$$DRAIN_j = (SW_j - DUL_j) \bullet RZDRF \bullet DLAYR_j. \tag{3-15}$$

RZDRF varies between 0 and 1 and is the fraction of the drainable water (water stored between drained upper limit and saturation) that drains from the root zone into the deeper soil layer on that that day. Finally, a new value of $SW_j$ after drainage is calculated:

$$SW_j = SW_j - DRAIN_j / DLAYR_j. \quad (3\text{-}16)$$

Case 2. If $FLUX_j$ is greater than $HOLD_j$, the root zone layer would reach saturation and drainage from the root zone layer, $DRAIN_j$ (mm $d^{-1}$), is calculated as follows:

$$DRAIN_j = (SAT_j - DUL_j) \cdot RZDRF \cdot DLAYR_j. \quad (3\text{-}17)$$

If $FLUX_j$ minus $DRAIN_j$ is smaller than $HOLD_j$, the new soil water content $SW_j$ after drainage is calculated from yesterday's soil water content and the net influx of water:

$$SW_j = SW_j + (FLUX_j\text{-}DRAIN_j) / DLAYR_j. \quad (3\text{-}18)$$

If $FLUX_j$ minus $DRAIN_j$ is greater than $HOLD_j$, implying that the root zone can not hold the entire downward flux of water even after drainage, the volumetric soil water content $SW_j$ is set to its maximum value $SAT_j$ and the surplus water is added to the drainage:

$$DRAIN_j = FLUXj - HOLD_j. \quad (3\text{-}19)$$

Water Flow to Streams

All surface runoff and lateral flow in the deeper soil is assumed to end up in a stream and eventually reach the outlet of the watershed. Partial evapotranspiration or infiltration of stream water and surface water along the flow path down is not considered. Movement of surface runoff and lateral flow to streams is modeled using a distributed delay.

Flow of surface runoff

The total amount of surface runoff from a land unit *j*, $TRO_j$ ($m^3 d^{-1}$), is equal to the runoff volume that was estimated by the SCS curve number method (Eq. 3-9) multiplied with the size of a land unit, AREA ($m^2$):

$$TRO_j = 0.001 \cdot AREA \cdot RO_j, \tag{3-20}$$

where 0.001 is the conversion factor from mm to m. Not all surface runoff originating from any land unit *j* will reach a stream within one day. If flow paths are long—in large watershed or if the stream density is relatively low—part of the surface runoff may reach a stream only after one or more day after rainfall occurs. This delay has been represented using a series of two imaginary "surface water compartments" for each land unit *j* (Figure 3-2). The storage capacity of these compartments is assumed unlimited. $SFW_j(X)$ is the water content in surface water compartment X of land unit *j* ($m^3$). The daily change in water content ($m^3d^{-1}$) in the first and second compartment is, respectively:

$$\Delta SFW(1)_j/\Delta t = TRO_j - DRAINSF_j(1), \quad \text{where} \tag{3-21}$$

$$DRAINSF(1) = (SFW(1)_j + TRO_j) \cdot SFWRT.$$

$$\Delta SFW(2)_j/\Delta t = DRAINSF_j(1) - DRAINSF_j(2), \quad \text{where} \tag{3-22}$$

$$DRAINSF_j(2) = (SFW(2) + DRAINSF(1)) \cdot SFWRT,$$

where SFWRT is the surface water retention factor. Its value is between 0 and 1 and allows controlling the characteristics of release of surface runoff flow into the stream. Lower values of SFWRT suppress peak flow rates and are applicable to relatively large and flat watersheds. Higher values of SFWRT are appropriate for field-scale areas and small mountainous watersheds with a rapid discharge of surface runoff.

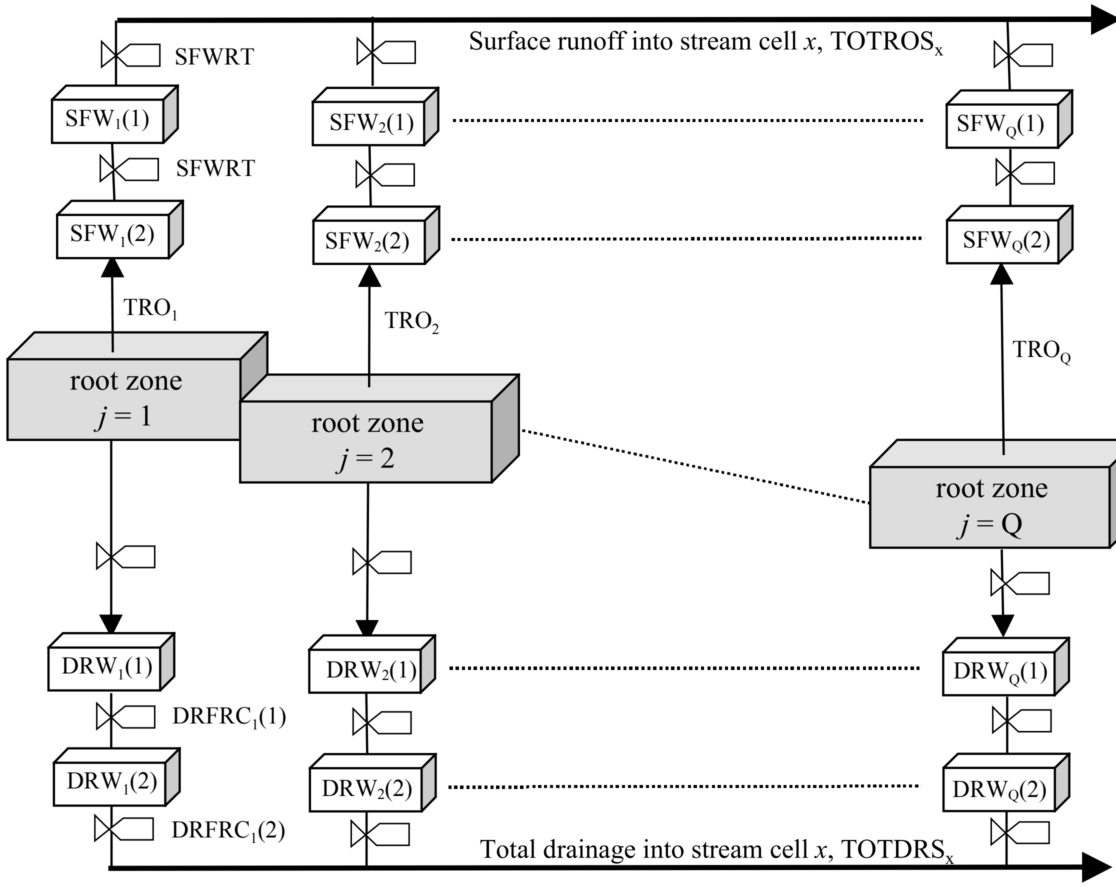



Figure 3-2. Representation of movement of surface runoff and drainage water from Q land units that form the contributing area to stream cell *x*, through a distributed delay of two surface water compartments and two drainage water compartments.

Figure 3-3 shows the fraction of an initial volume of surface runoff that is discharged in the river for SFWRT values of 0.3, 0.5, 0.7 and 0.9. This figure illustrates that different SFWRT result in different patterns of surface runoff discharge. Note that a fraction $SFWRT^2$ of $TRO_j$ is transferred through both compartments and reaches a stream on the first day ($t$=0).

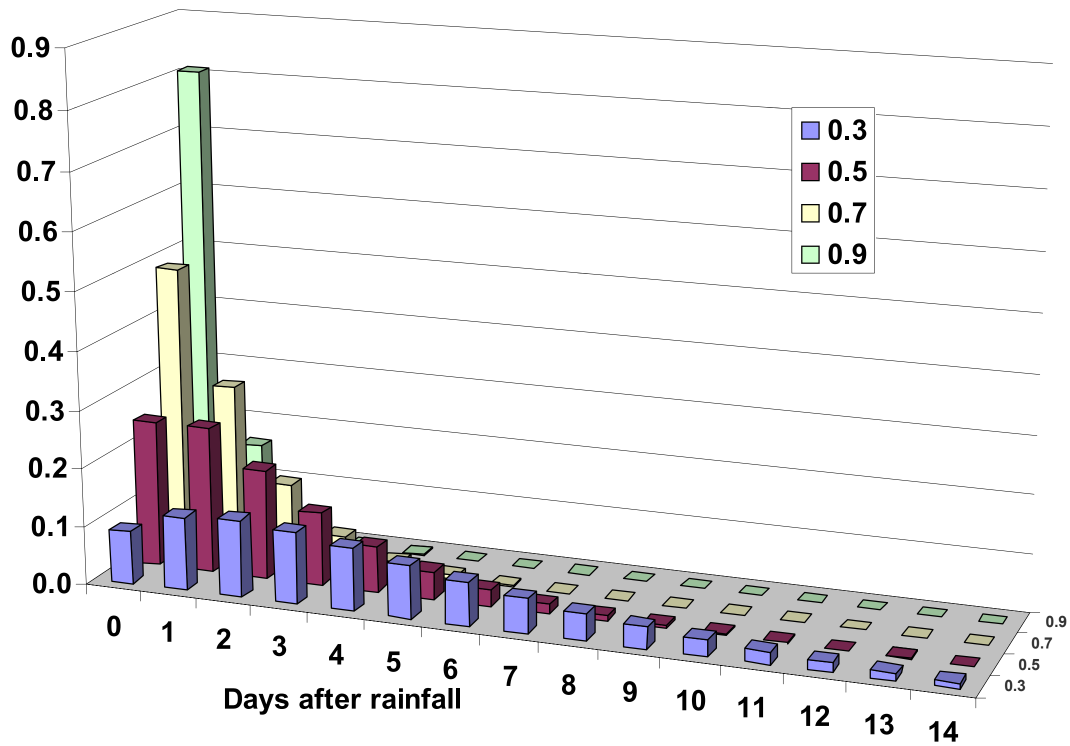



Figure 3-3. Fraction of total surface runoff that is released into the river after a rainfall event, for four different values of the surface water retention factor, SFWRT.

Release of water out of the second compartment, $DRAINSF_j(2)$ (in $m^3d^{-1}$), is the run-off volume that actually reaches a stream on that particular day. The total rate of surface runoff into stream cell *x*, $TOTROS_x$ (in $m^3d^{-1}$), is given by:

$$TOTROS_x = \sum_{j=1}^{Q} DRAINSF_j(2) \tag{3-23}$$

where *Q* is the total number of land units *j* that form the contributing area (catchment area) of stream cell *x*. The contributing area to each stream cell is calculated from a Digital Elevation Model (DEM) using standard GIS algorithms (see Appendix B).

Lateral flow in the deeper soil

Lateral flow in the deeper soil layer is the second contributing factor to stream water. Chapter 2 explained a simplified drainage and lateral flow model that described movement of soil water to streams using a 2-compartment distributed delay. The model was applied to a single hill slope. The area of application can easily be extended to an entire watershed by considering a watershed as a set of two or more parallel hill slopes in which a network of two or more connected stream cells is located. Because of spatial variation in topography and soil characteristics, the different hill slopes may have different average slopes along the flow path ($SLOPE_{AV,j}$, Eq. 2-7), average hydraulic conductivities ($K_{AV,j}$, Eq. 2-7) along the flow path, and different maximum flow lengths (FLOWLMX, Eq. 2-7).

The daily drainage from each hill slopes into the stream must be computed. For each stream cell *x*, the rate of drainage water flow (lateral flow) into the stream cell, $TOTDRS_x$ ($m^3d^{-1}$) (see Figure 3-2), is estimated by the total drainage rate of the second-level drainage water compartment of all contributing land units:

$$TOTDRS_X = \sum_{j=1}^{Q} DRFRC_j(2) \cdot DRW_j(2), \tag{3-24}$$

where *Q* is the total number of land units *j* that are part of the contributing area of stream cell *x*, $DRW_j(2)$ is the water content in second drainage water compartment X ($m^3$) of land unit *j*, and $DRFAC_j(2)$ is the daily drainage fraction of the second drainage water compartment of land unit *j*, which is computed with Equation 2-11. Note the similarity between Equations 3-23 and 3-34. The value of Q and contributing area to each stream cell are identical in both equations because the direction of surface runoff and lateral flow is assumed the same, based on a Digital Elevation Model (DEM). The contributing area to each stream cell is calculated from a DEM using standard GIS algorithms (see Appendix B).

<u>Stream Water Flow Balance</u>

In a raster GIS, a stream is represented by a series of connected grid cells, each of which receives an accumulated flow beyond some threshold. A stream network consists of one or more stream branches. Figure 3-4 shows the components of the water balance for a stream cell. Water in a stream is assumed to flow sufficiently fast so that water that enters the stream at any point in the watershed will reach the outlet within a day, unless it is (temporarily) stored in a dam or used. This is a reasonable assumption for small watersheds in hillside regions. It has the advantage that the stream water balance for the entire watershed can be calculated using total daily flow volumes. For watersheds that are larger than approximately 100,000 ha, the effect of this assumption should be evaluated.

Any stream cell *x* may be the location of a dam with a specific storage amount $ST_x$. Stream cells *x* that are not dams are assumed to have a zero storage capacity. A water tank, pond or reservoir external to the stream may be connected to the dam to have water available in the immediate proximity of houses or fields. SWBM does not distinguish between dams and external water storage. The physical dimensions of a dam required to realize the specified storage capacity and the construction and daily operation of dams are engineering aspects that are assumed technically feasible but are not taken into account by SWBM.

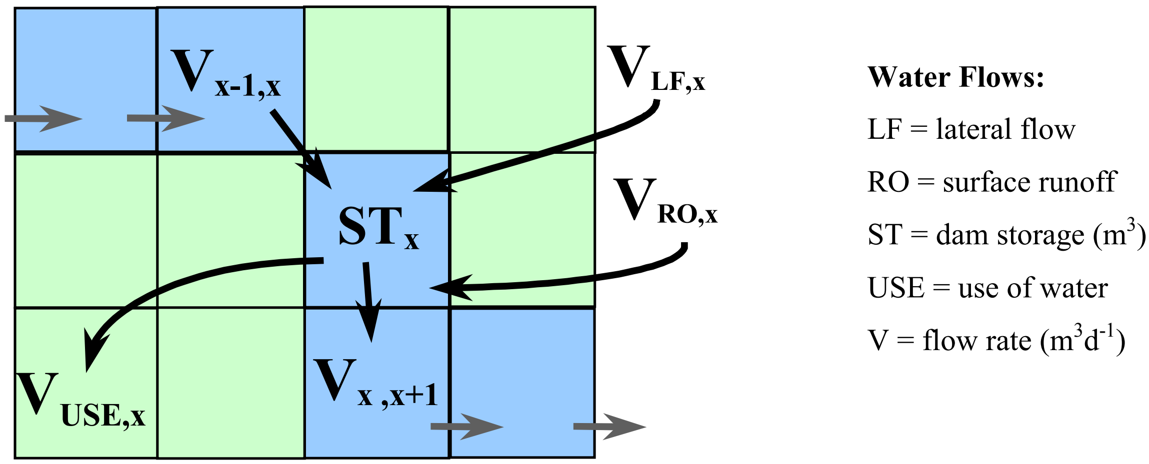



Figure 3-4. Representation of a stream in a raster GIS and components of the stream water balance. The stream cells are blue colored and the land units are green colored.

If a stream is considered as a series of *N* connected grid cells, with grid cell *N* being the watershed outlet (the lowest point in the watershed), then the daily water volume that flows from stream cell *x* to the adjacent downstream cell *x+1* (with $0<x<N$) is

$$V_{x,x+1} = V_{x-1,x} + V_{RO,\,x} + V_{LF,\,x} - V_{USE,\,x} - \Delta ST_x \tag{3-25}$$

where $V_{x-1,x}$ is the water volume that flows from the neighboring upstream stream cell to stream cell *x*; $V_{RO,\,x}$ and $V_{LF,\,x}$ are the accumulated rates of, respectively, surface runoff and lateral flow into stream cell *x* from adjacent land units; $V_{USE,\,x}$ is the daily volume of water extracted from stream cell *x* to meet water demands, and $\Delta ST_x$ is the change in storage in stream cell *x* if that cell has a dam. Note that $V_{0,1}$ is always zero (beginning point of a stream) and that $V_{N,N+1}$ is the daily volume of water that flows out of the watershed. The unit of all terms in Equation 2-32 is $m^3d^{-1}$.

The terms $V_{RO,\,x}$ and $V_{LF,\,x}$ in Equation 3-25 are calculated from, respectively, the total volume of surface runoff and lateral flow that reaches stream cell *x* and its adjacent upstream cell *x*-1:

$$V_{RO,\,x} = TOTROS_x - TOTROS_{x-1}, \quad \text{and} \tag{3-26}$$

$$V_{LF,\,x} = TOTDRS_x - TOTDRS_{x-1}. \tag{3-27}$$

Typically, the water extraction term ($V_{USE,\,x}$) in Eq. 3-25 is zero for most stream cells, except at a number of specific locations (for example, at places where the stream is close to a house or where there is a water pump). Water extraction rates may vary between these locations and may change over time as well. Modeling of daily water extraction and the daily operation of dams are explained in detail in Chapter 4.

## Model Implementation and Data Requirements

The SWBM model has been written in Avenue (ESRI, 1996a). It runs on Windows and Unix based systems using the ArcView GIS v3.1 software (ESRI, 1997b) with the Spatial Analyst v1.1 and Dialog Designer extensions. The ArcView GIS interface facilitates all input of data through menus. Simulation results, which are saved in ARC/INFO grids and in dBase-IV files, are processed using Avenue scripts and spreadsheet software.

The SWBM model has been developed for application in agricultural hillside watersheds in Latin America and the Caribbean for which typically few biophysical data are available. Data requirements are relatively low compared to those of other distributed parameter models like ANSWERS2000 (Dillaha et al., 1998) and AnnAGNPS (Bosch et al., 1998). Data are either inputted as ARC/INFO grids or entered through user-friendly menus and automatically stored in the correct format in dBase IV files. The ARC/INFO GRID software (ESRI, 1994) has been used to create these grids in the correct format and projection. All grids must have the same spatial extent, projection and cell size. Appendix D provides details on the required input data.

# Materials and Methods

## Data

### Topography

In a Geographic Information System, a Digital Elevation Model (DEM) has become a standard way of representing surface elevation over an area. DEMs were originally computed as the precursor of orthophotos, but today they have many other applications (Burrough and McDonnell, 1998). DEMs are modeled by regular grids (altitude matrices) and Triangular Irregular Network (TIN). Both data types are inter-convertible, but altitude matrices are the most common type.

CIAT created an altitude matrix DEM for the larger Ovejas River watershed (in which the Cabuyal River watershed is located) by digitizing existing 25 m contour maps. Figure 3-5 shows part of this DEM. The resolution of this DEM was 25 m. Using the ARC/INFO GRID software (ESRI, 1994), I resampled the DEM to a 100 m resolution grid using a weighted distance interpolation method. This resulted in a relatively faster simulation while providing an adequate representation of the topography. The resampled DEM was filled to remove any topographic depressions (sinks) that were added by the resampling process. Once completed, the direction of surface flow, locations of streams, and the length of flow paths from all land units to streams were determined from the DEM. Finally the catchment area of the Cabuyal River was clipped out of all grids. Appendix B gives an overview of the algorithms for GIS-based hydrological analysis and filling DEMs.

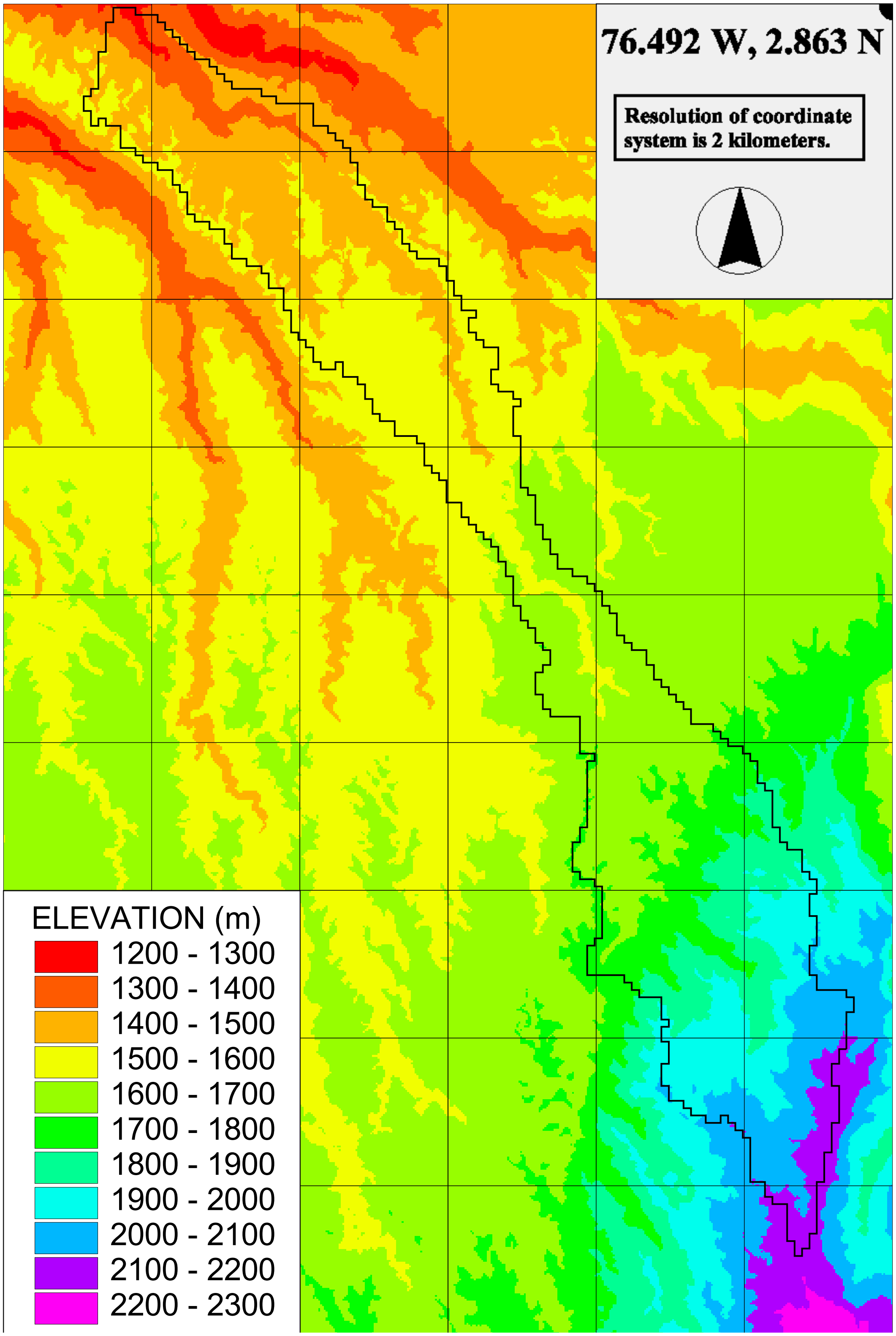



Figure 3-5. Digital Elevation Model (DEM) of a 12 by 18 km area around the 3,246 ha Cabuyal River watershed. Boundaries of the watershed have been delineated.

Soils

The soils in the Cabuyal River watershed are Inceptisols from volcanic origin. They belong to five different groups (with common local name and percentage of area covered): Oxic Dystropept (Pescador, 42.4%), Typic Placandept (Usendor, 26.2%), Ustic Dystropept (Suarez, 16.7%), Typic Humitropept (Farallones, 14.1%) and Tropic Fluvaquent (Puelenge, 0.6%). Figure 3-7 shows a soil map of the Cabuyal River watershed.

The soils throughout the watershed have a high percentage of oxidized iron (which causes a red color), low pH, high organic C content, are P deficient, and have low bulk densities. Hansen (1996) analyzed soil samples from eight different locations on the Jose Domingo farm in the middle of the watershed (see Figure 3-8) and measured a bulk density between 0.42 and 0.45 g $cm^{-3}$ for a Pescador soil. Knapp (1994, unpublished data) reported bulk densities between 0.40 and 0.60 g $cm^{-3}$ based on samples taken at the Domingo, Losada and Trujillo farms in the Cabuyal River watershed. Infiltration rates were generally high and the saturated hydraulic conductivity was in the order of 5-6 cm $h^{-1}$ (Hansen, 1996; Revelo et al., 1994). Despite the rapid movement of drainage water, the soils retain water very well.

The volumetric soil water contents at wilting point (WP), drained upper limit (DUL) and saturation (SAT) are needed for the calculation of the root zone water balance. Table 3-3 gives these critical water contents based on analysis of measurements taken that Hansen (1996) took in the Cabuyal River watershed. The plant extractable water holding capacity (DUL-WP) varies from 0.113 to 0.166 $cm^3cm^{-3}$. I used values of WP=0.35, DUL=0.46 and SAT=0.56 $cm^3cm^{-3}$ for the entire soil root zone. A hydraulic conductivity of 1 m $d^{-1}$ was used. These values have been applied uniformly over the entire watershed because there were no spatially variable soil data.

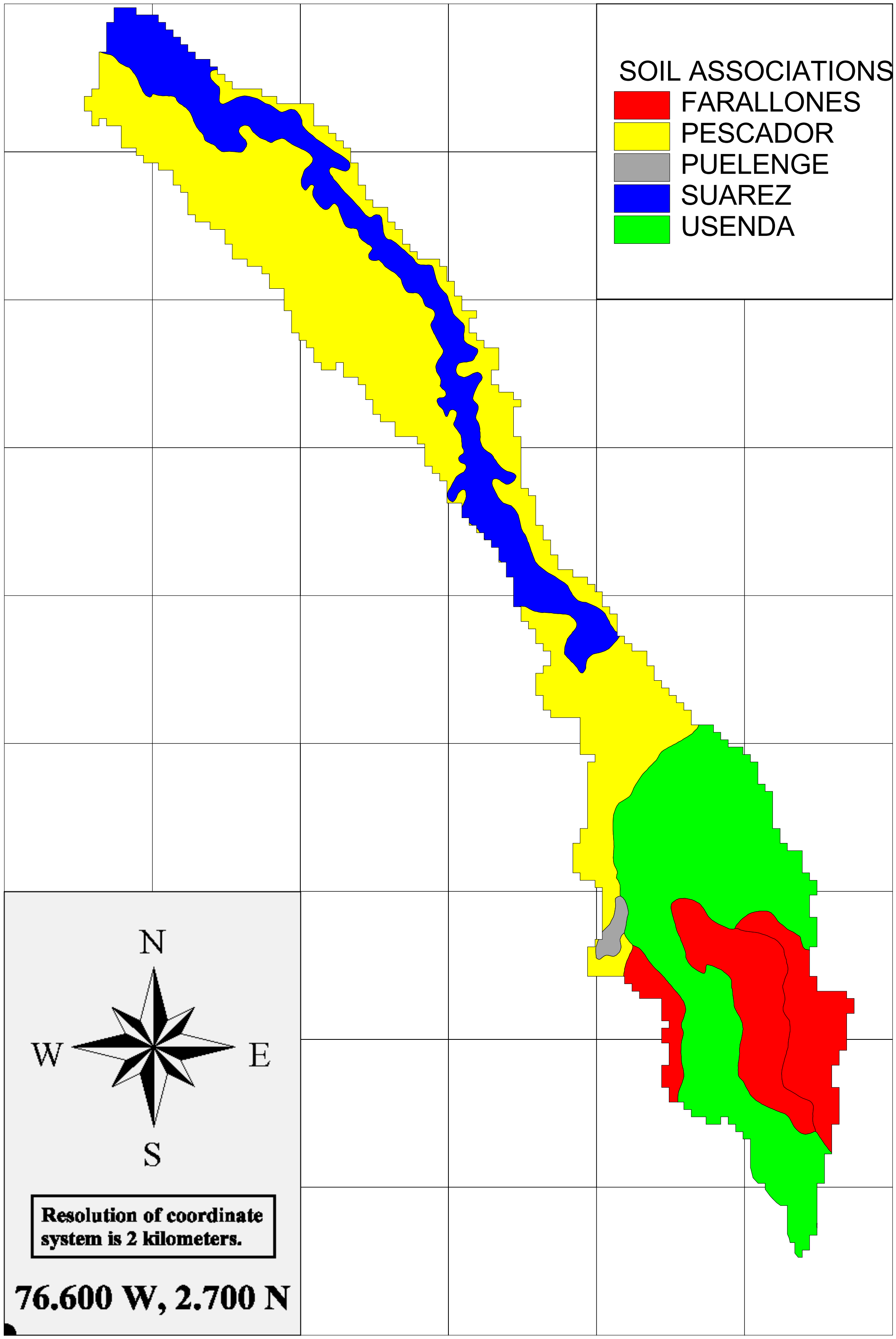



Figure 3-6. Soil associations within the 3,246 Cabuyal River Watershed, Colombia.

Table 3-3. Soil water content at wilting point (WP), drained upper limit (DUL) and saturation (SAT), based on soil analysis in the Cabuyal River watershed.

| Location | Depth (cm) | WP | DUL | SAT |
|---|---|---|---|---|
| | | ------------- volume fraction ---------- | | |
| Domingo Farm [1] | 20-25 | 0.325 | 0.467 | 0.575 |
| | 50 | 0.375 | 0.541 | 0.622 |
| | 200 | 0.375 | 0.541 | 0.622 |
| Pescador Series [2] | 15-25 | 0.124 | 0.250 | 0.361 |
| | 30-40 | 0.116 | 0.242 | 0.362 |
| | 65-75 | 0.347 | 0.460 | 0.475 |
| | 165-75 | 0.320 | 0.434 | 0.449 |
| | 205-220 | 0.338 | 0.451 | 0.466 |

[1] Source: Hansen (1996) and Hansen et al. (1997)
[2] Source: J.W. Hansen, 1997, personal communication.

The depth of the soil profile is not needed by SWBM because the deeper soil layer is not modeled based on physical processes. There is little information on the depth of the soil profile in the Cabuyal River watershed. Rubiano (1999, personal communication) measured the depth of the rock bed at a few locations in the watershed and found that it varied from less than 0.5 m near rivers to over 2 m further from streams. It was assumed that soils are generally deep enough to allow roots to grow freely and reach the average depths that are given in Table 3-11.

At the beginning of the simulation, the soil water content in the root zone was set to drained upper limit for the entire watershed. It is critically important that reasonable initial water volumes for the drainage water compartments are chosen. Wrong initial values may result in serious under- or over-estimation of drainage rates and river flow rates. These initial water volumes were automatically computed by SWBM such that the resulting river flow rate was equal to the average flow rate of during that time of the year (see Table 3-10). SWBM allows starting the simulation some time (several weeks or months) prior to the desired simulation period so that soil water content can adjust from any incorrect initial settings. All processes are simulated during this initial period, but results are not saved.

Land use/land cover (LUC)

Two different land use/land cover (LUC) data sets were available for the watershed. The first data set was a maximum likelihood classification of a Landsat 4 Thematic Mapper (TM) image from August 9, 1989. Langford and Bell (1997) resampled the TM image from 30 to 10m resolution and classified a 15 by 20 km region (longitude 2.688° N – 2.869° N and latitude 76.610° W – 76.475° W) of the TM image. The classification consisted of ten land use types.

The accuracy of the classification is about 35%. This is relatively poor compared to figures of around 80-90% often reported in research literature for other environments. Langford and Bell (1997) argue that the low accuracy is simply a reflection of how difficult it is to map an extremely fragmented landscape with a complex topography using 30 m resolution satellite imagery. No correction for topographic effects was performed, which may be another reason for the low accuracy. Changes in topography result in irregularly illuminated areas and in variation in light reflection geometry (Conese et al., 1993). Ideally, remotely sensed data should be corrected for these effects, accounting for the actual solar incidence angles. Several techniques have been proposed for the topographic correction (Meyer et al., 1993; Ekstrand, 1996; Conese et al., 1993). All techniques require a digital elevation model to calculate the slope and aspect of the landscape. Although I did have the original TM image and a DEM of the 15x20 km region, I was unable to perform the topographic correction and reclassify the image because the 1989 ground reference information was not available.

Using ARC/INFO GRID software (ESRI, 1994), I resampled the LUC classification from 10 m to 100 m resolution using a maximum area criterion, i.e. the land use type that had the highest frequency in the 100 smaller grid cells was assigned to the aggregated grid cell, and clipped out the actual catchment area. Figure 3-7 shows the resulting land use map.

The second LUC data set was a classification based on air photography. This data set were available for the years 1946, 1970, 1989 and 1994 as ARC/INFO coverages (Rubiano, 1998; Knapp et al., 1996). The air photo classification suffered from its coarse resolution and lack of any statistics on accuracy. The coarse resolution was a result of the fact that a minimum area of 3 ha was used for land units (a polygon) during the photo interpretation (Knapp et al. 1996). I focussed on the 1989 classification because it is the same year as the Landsat TM-based classification. There are 11 different LUC types. A visual inspection of the maps showed that some LUC units seem unrealistically large, such as the large area of unmanaged pasture in the south of the watershed. Using ARC/INFO GRID software, I converted the 1989 land use coverage to a grid and clipped out the actual watershed. If a grid cell had more than one possible LUC type (i.e., it contains two or more polygons), the LUC type of the polygon with the greatest area in the cell was used. The land use map is shown in Figure 3-8.

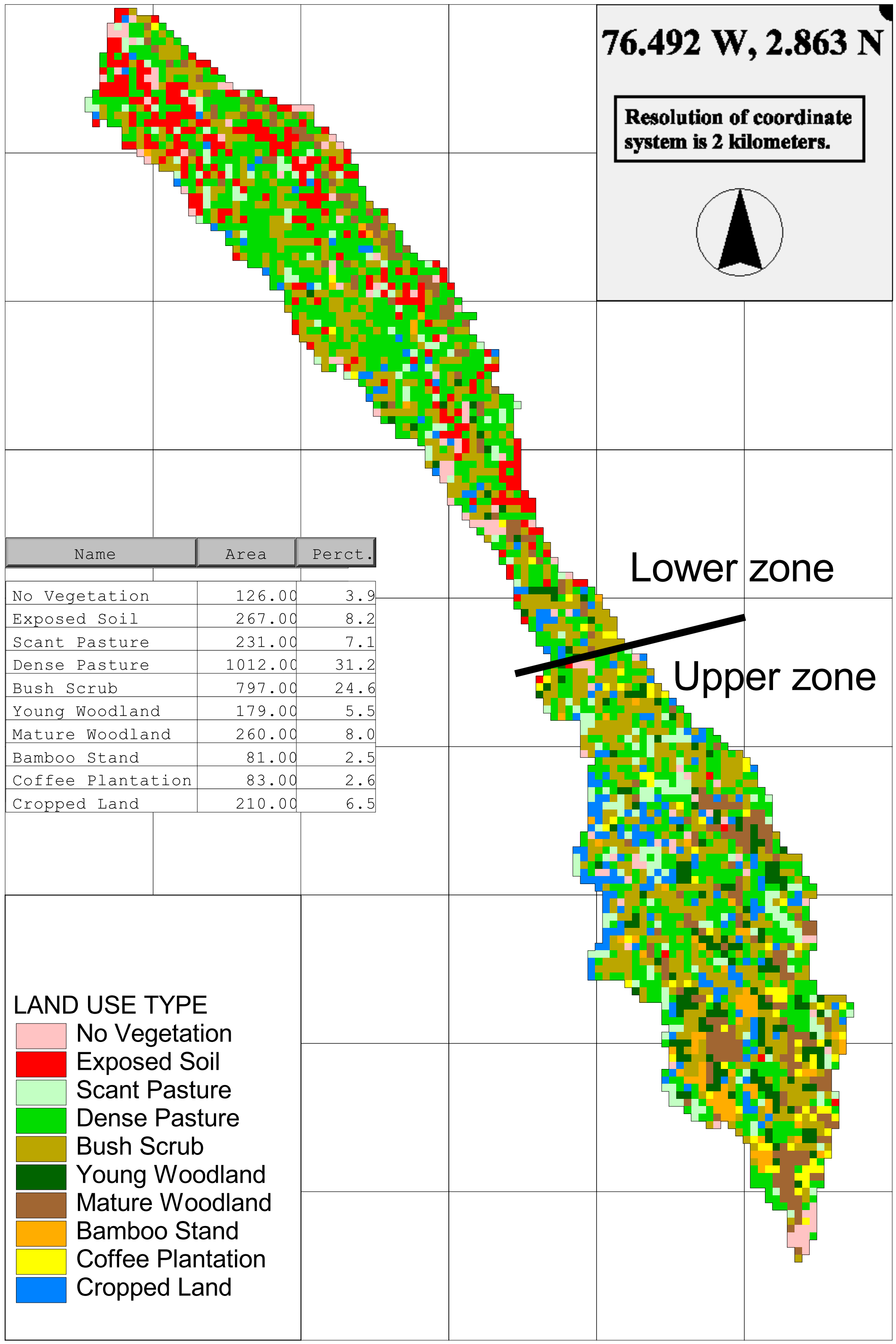
The land use classifications in Figures 3-7 and 3-8 show little similarity. The land use classes are different, and even land use classes that have similar names, appear different on the map. For example, Fig. 3-7 shows coffee only in the south whereas Fig. 3-8 shows major coffee plantations in the north of the watershed. Also, the areas of *No Vegetation* and *Exposed Soil* that are found in the north of the watershed on Fig. 3-7 are not present in Fig. 3-8.

I selected the Landsat TM based land use classification for this work. Table 3-4 gives the land use types and the areas covered by them in the lower and upper part of the watershed. The upper part of the watershed is defined as the catchment area of the Cabuyal river at the point 76° 31' 43" W and 2° 46' 54" N. This is immediately downstream from the intersection point of the two major streams in the upper part of the watershed. The catchment area of the Cabuyal River at this point is 1,662 ha, 51% of the watershed.

Table 3-4. Areas (ha and %) covered by each land use type in the lower and upper zones of the watershed, and for the watershed as a whole, based on classification of a 1989 Landsat 4 Thematic Mapper image, resampled to 100 m resolution.

| Land use type | Lower zone (ha) | Upper zone (ha) | Total (ha) | Percent |
|---|---|---|---|---|
| No Vegetation | 75 | 51 | 126 | 3.9% |
| Exposed Soil | 261 | 6 | 267 | 8.2% |
| Scant Pasture | 89 | 142 | 231 | 7.1% |
| Dense Pasture | 615 | 399 | 1012 | 31.2% |
| Bush Scrub | 357 | 440 | 797 | 24.6% |
| Young Woodland | 26 | 153 | 179 | 5.5% |
| Mature Woodland | 87 | 173 | 260 | 8.0% |
| Bamboo Stand | 10 | 71 | 81 | 2.5% |
| Coffee Plantation | 10 | 73 | 83 | 2.6% |
| Cropped Land | 56 | 154 | 210 | 6.5% |
| Total | 1584 | 1662 | 3246 | 100% |

Land use is considerably different in the upper and lower parts of the watershed. Most woodland, coffee plantation and cropped land can be found in the upper part, whereas the lower part has more dense pasture and virtually all of the exposed soil.




| Name | Area | Perct. |
|---|---|---|
| No Vegetation | 126.00 | 3.9 |
| Exposed Soil | 267.00 | 8.2 |
| Scant Pasture | 231.00 | 7.1 |
| Dense Pasture | 1012.00 | 31.2 |
| Bush Scrub | 797.00 | 24.6 |
| Young Woodland | 179.00 | 5.5 |
| Mature Woodland | 260.00 | 8.0 |
| Bamboo Stand | 81.00 | 2.5 |
| Coffee Plantation | 83.00 | 2.6 |
| Cropped Land | 210.00 | 6.5 |

Figure 3-7. Land use in 1989 in the Cabuyal River watershed, Colombia, classified from a Landsat 4 Thematic Mapper image, at 100 m resolution.

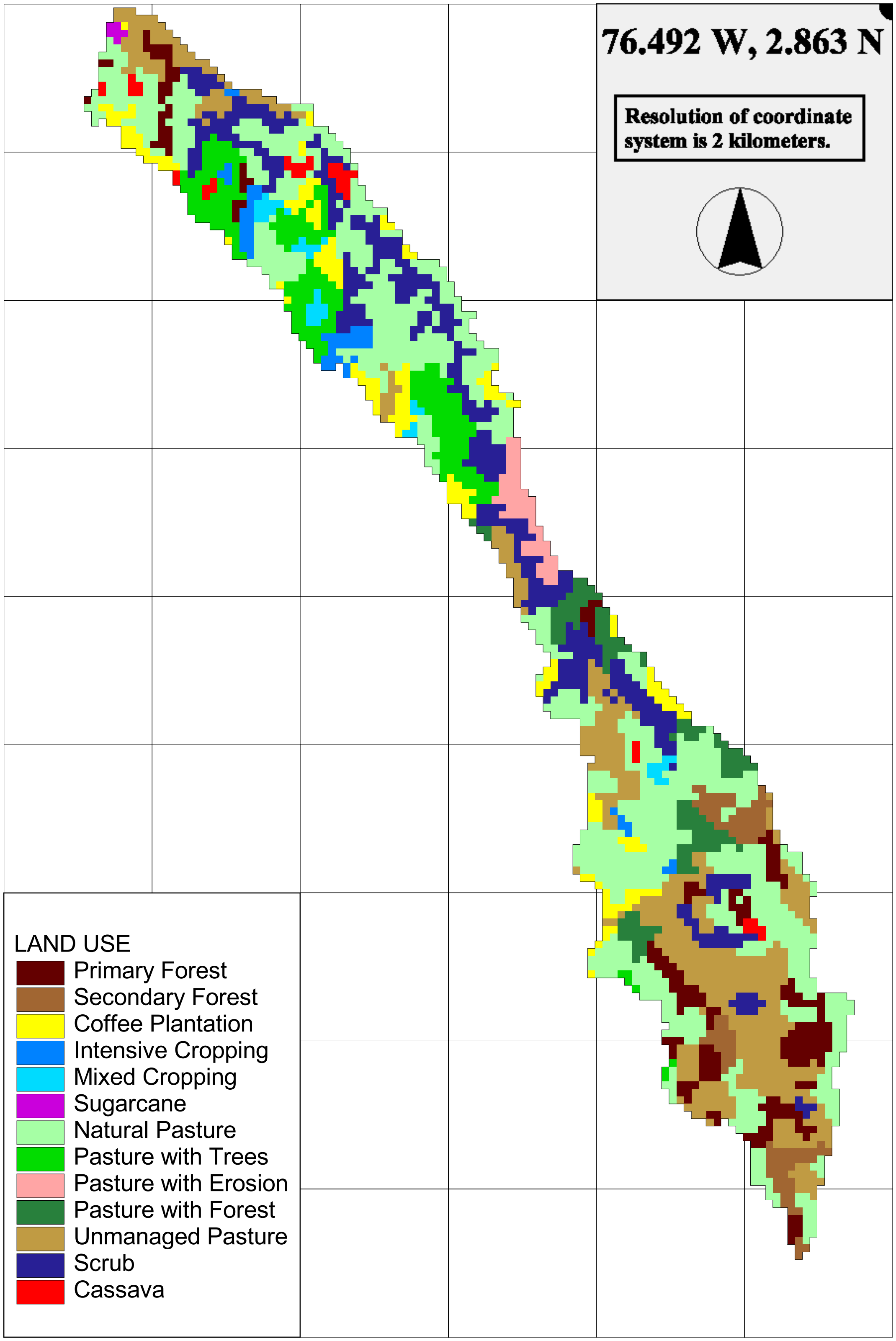



Figure 3-8. Land use in 1989 in the Cabuyal River watershed, Colombia, based on air photograph interpretation, at 100 m resolution.

Weather

Starting in November 1993, weather data have been collected at four locations in the Cabuyal River watershed (Figure 3-9) using two different methods. Key characteristics of each weather station are given in Table 3-5. At three locations, the farmers recorded minimum and maximum daily temperature from a portable thermometer and rainfall from a plastic rain gauge. Three out of four locations also had an automatic weather station where solar radiation, minimum and maximum temperatures and rainfall were recorded by a LI-COR minimum data set weather station (Hansen, 1996). On June 24, 1998, none of the automatic weather stations was operational anymore. Automatically collected data from August 1997 to June 1998 was lost for all three stations because of equipment failure and because data had not been downloaded on a regular basis.

Table 3-5. Weather stations in the Cabuyal River watershed. The last two columns indicated whether weather data were manually recorded (HAND) or automatically collected (AUTO). The periods for which data are available vary between the locations.

| Location, Community | Longitude | Latitude | Altitude | AUTO | HAND |
|---|---|---|---|---|---|
| Domingo farm, Ventenas | 76.527 W | 2.789 N | 1659 m | yes[1] | yes |
| Trujillo farm, La Campina | 76.560 W | 2.818 N | 1550 m | yes | no |
| Finca farm, El Oriente | 76.511 W | 2.736 N | 1976 m | yes | yes |
| San Idriso Interprogram, Pescador | 76.555 W | 2.800 N | 1497 m | no | yes |

[1] The periods for which weather data were collected vary among the weather stations.

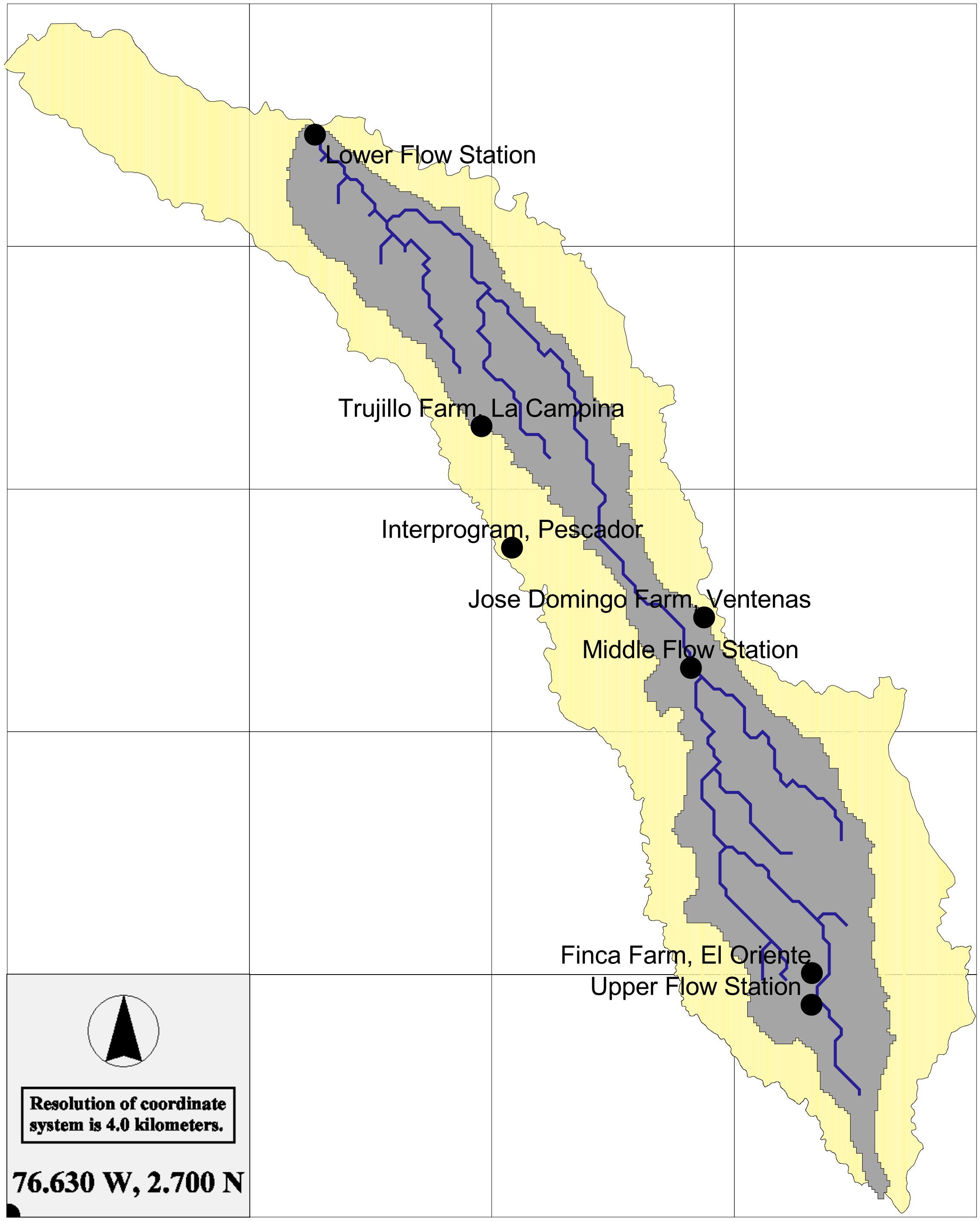



Figure 3-9. Locations of four weather stations and three sites where flow measurements were taken in the Cabuyal River watershed. The dark shaded area indicates the watershed. The light shaded area is the administrative Cabuyal region.

The most complete set of weather data was from the Domingo farm. Although there were several periods with missing data in both the manually recorded data and the data from the LI-COR station, combining both data sets resulted in a daily weather data set for nearly five years. Rainfall data were available from November 1, 1993 through November 20, 1998, minimum and maximum temperatures from November 1, 1993 through July 15, 1998, and solar radiation from April 14, 1994 through August 25, 1997. I used data for the calendar years 1994-1997. Missing solar radiation for the last four months of 1997 was estimated using the Weatherman software (Pickering et al., 1994). Manually recorded rainfall agreed closely with the data from the tipping bucket rain gauge for periods for which both were available. However, maximum temperatures recorded by the LI-COR station were on average 4° C higher than those measured by the portable thermometer. The discrepancy might have been caused by the location of the portable thermometer in a shaded area under the roof of the porch of the house (Hansen, 1996). Manually recorded maximum temperatures were adjusted by increasing them by 4°C. Differences between the two sets of minimum temperature data were small. Table 3-6 presents the monthly and annual rainfall measured at the Jose Domingo farm from November 1993 through September 1998. The dry season runs from June till September. All other months were relatively wet, with the highest rainfall occurring in October-December and second wet period in March-April.

Average monthly rainfall measured at the Domingo farm was compared with two sets of long-term average monthly rainfall measured at weather stations nearby, but outside the Cabuyal River watershed (Table 3-7). The first set of data were averages based on 25 years (1974-1988) of daily data from five weather stations in the Ovejas River watershed (Morales, El Amparo, Piendamo, Mondomo, and La Aguada) (de Fraiture et al., 1997), to which the Cabuyal River watershed is a tributary. Annual rainfall at the Domingo farm in the years

1994 through 1997 was respectively 13.7%, 25.7%, 23.9% and 29.9% lower than the long-term average annual rainfall in the Ovejas River watershed. Also, the dry period lasted longer than usual in these four years because rainfall in August, September, October and November was below the corresponding long-term monthly averages. The second data set was based on 37 years (1950-1986) of daily data from the La Florida weather station in Popayan (76.58 W; 2.43 N; elevation 1,850 m), approximately 40 km south of the Domingo farm. Differences in monthly and annual rainfall measured at the Domingo and La Florida stations are smaller.

Table 3-6. Monthly rainfall (mm) measured at the Domingo farm weather station.

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1993 | - | - | - | - | - | - | - | - | - | - | 222 | 238 | - |
| 1994 | 328 | 71 | 281 | 206 | 254 | 67 | 49 | 9 | 59 | 179 | 215 | 191 | 1908 |
| 1995 | 125 | 30 | 146 | 312 | 115 | 98 | 120 | 60 | 53 | 221 | 160 | 202 | 1642 |
| 1996 | 219 | 151 | 226 | 165 | 119 | 52 | 69 | 36 | 70 | 159 | 190 | 227 | 1682 |
| 1997 | 262 | 101 | 202 | 212 | 135 | 178 | 5 | 0[1] | 126 | 112 | 191 | 105 | 1556 |
| 1998 | 97 | 160 | 202 | 212 | 351 | 75 | 63 | 112 | 113 | 145 | - | - | |

[1] No precipitation was (manually) recorded from July 10 to August 30, 1997. It is not clear if this was caused by a broken rain gauge or that no rainfall occurred during this period.

Table 3-7. Monthly average and annual rainfall (mm) from the Domingo farm weather station (11/93 – 9/98), five weather stations in the Ovejas River watershed (1/1974 - 12/1988), and the La Florida weather, Popayan (1/1950 - 12/1986).

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Domingo | 206 | 103 | 208 | 211 | 195 | 94 | 61 | 43 | 84 | 163 | 195 | 193 | 1760 |
| Ovejas | 191 | 201 | 225 | 250 | 213 | 91 | 75 | 87 | 130 | 283 | 268 | 197 | 2211 |
| LaFlorida | 169 | 158 | 188 | 192 | 153 | 95 | 43 | 48 | 103 | 268 | 286 | 267 | 1970 |

Stream flow measurements

Ideally, several years of daily flow data should be available to adequately calibrate and verify a hydrological model. The only available flow measurements from the Cabuyal River were taken at three different locations in the watershed on eight different days in 1995 and 1996 (Table 3-8) (de Fraiture et al, 1997). The lower flow measurement location is 100 m upstream from where the Cabuyal River merges into the Ovejas River (76.584° W; 2.861° N). The middle flow measurement location is where the two main streams from the upper part of the watershed merge (76.529° W; 2.782° N). The catchment area of the river is 1,662 ha here, 51.2% of the watershed. The upper flow measurement location is 100 m downstream from the intake of the main drinking water system (76.511° W; 2.732° N). Figure 3-9 shows the locations were flow measurements were taken.

Table 3-8. Measured flow rates ($m^3s^{-1}$) at three different locations in the Cabuyal River.

| | 4/29/94 | 9/13/94 | 10/3/94 | 4/30/95 | 8/9/95 | 10/19/95 | 9/23/96 | 10/25/96 |
|---|---|---|---|---|---|---|---|---|
| Lower site | 1.36 | 0.29 | 0.54 | 1.21 | 0.52 | 0.56 | 0.27 | 0.39 |
| Middle site | 0.75 | 0.13 | 0.30 | 0.51 | 0.24 | 0.28 | - | - |
| Upper site | 0.31 | 0.07 | 0.15 | 0.28 | 0.12 | 0.16 | - | - |

Source: de Fraiture et al. (1997).

Average monthly flow data from the Ovejas River were available for the years 1965 through 1988. Daily flow data were only available for 1974 through 1988, with the exception of 1983 (which were lost). These daily and monthly flow data are given in Appendix E. These data indicated that flow rates are lowest in mid September. Monthly average flow rates of the Cabuyal River were estimated by multiplying the monthly average flow rates of the Ovejas River by the ratio of the catchment areas of each (3,246 / 61,500). Monthly average flow rates for the Ovejas and Cabuyal rivers are given in Tables 3-9 and 3-10, respectively

Landscape characteristics (such as land cover, topography, and soil) of the Ovejas River watershed are quite similar to those of the Cabuyal River watershed. Assuming that both watersheds have similar hydrologic behavior, the Ovejas River flow data were used to calibrate hydrograph characteristics of the model, in particular the base flow index (BFI, ratio of base flow to total stream flow) and surface runoff retention parameters. De Fraiture et al.

(1997) estimated the long-term average BFI for the Ovejas River at 0.77. This is relatively high value, indicating that as much as 77% of the net precipitation infiltrated and reached the river as base flow (slow flow through the soil). The remaining 23% of rainfall was surface runoff. The BFI can vary considerably throughout the year, depending on the frequency and intensity of rain events and soil water content.

Table 3-9. Minimum, mean and maximum monthly flow rates ($m^3s^{-1}$) for the Ovejas River, based on 24 years (1965-1988) of flow measurements.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min. | 14.3 | 14.8 | 15.3 | 14.8 | 16.6 | 12.4 | 8.6 | 6.8 | 5.9 | 7.3 | 13.7 | 17.2 | 5.4 |
| Mean | 21.8 | 22.8 | 22.5 | 22.9 | 24.1 | 16.9 | 11.2 | 8.5 | 8.2 | 14.1 | 25.6 | 26.6 | 18.8 |
| Max. | 55.4 | 61.1 | 65.1 | 63.4 | 61.0 | 38.2 | 21.7 | 19.5 | 24.5 | 52.3 | 70.5 | 68.8 | 120.7 |

Table 3-10. Minimum, mean and maximum monthly flow rates ($m^3s^{-1}$) for the Cabuyal River, estimated from Ovejas River flow data in Table 3-9.

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Min. | 0.76 | 0.78 | 0.81 | 0.78 | 0.88 | 0.65 | 0.45 | 0.36 | 0.31 | 0.39 | 0.72 | 0.91 | 0.29 |
| Mean | 1.15 | 1.21 | 1.19 | 1.21 | 1.28 | 0.89 | 0.59 | 0.45 | 0.44 | 0.75 | 1.35 | 1.40 | 0.99 |
| Max. | 2.93 | 3.23 | 3.44 | 3.35 | 3.22 | 2.02 | 1.15 | 1.03 | 1.30 | 2.76 | 3.73 | 3.63 | 6.38 |

## Model Calibration

Model calibration is the process of systematically adjusting model parameters to obtain the best fit between simulated results and measurements on the real system. Estimates of model parameters should be consistent with actual watershed characteristics. The goodness of fit criterion may be a subjective judgement on adequacy, a statistic selected to measure goodness of fit, or some multi-objective function combining several statistics (Haan et al., 1982). Compared to the calibration of a lumped parameter model, adequate calibration of a comprehensive distributed parameter model is generally a difficult task or may even be impossible. Many developers and users of these models provide detailed results on the input preparation and evaluation of a distributed parameter model for a case study watershed, but give little information on model calibration (for example, Srinivasan and Arnold, 1994; Hayes and Zhang, 1998). Efforts to calibrate the AnnAGNPS model seem to focus exclusively on adjusting SCS curve numbers (Bosch et al., 1998), which is one of the most important parameters affecting runoff volumes. Bouraoui and Dillaha (1994) stated that the ANSWERS2000 model is intended for use without any calibration.

From these findings it should not be concluded that calibration of distributed parameter models is not important. However, distributed parameter models have a number of characteristics that pose problems for the calibration process. First, many model parameters represent spatially variable characteristics of the landscape, such as elevation, hydrological soil properties, land use/land cover type, and the dimensions of stream channels. Adjusting these parameters implies a diminished representation of the real system, which is opposite of the calibration objective. Secondly, a distributed parameter model has a large number of parameters because many parameters are actually sets of parameters, one for each land unit. It may be impossible or undesirable to evaluate each and every possible combination of parameter values. Thirdly, in order to test the goodness of fit for each land unit, key system variables should be measured at each land unit. This would require an enormous amount of equipment and time, which may only be available at experimental watersheds.

These issues have been considered in the calibration of the SWBM for the Cabuyal River watershed. The watershed is not an experimental watershed. Relatively few data were available for parameterization of the model. Therefore, a simple calibration procedure has been used to obtain acceptable simulated stream flow volumes at the outlet of the watershed (for the watershed as a whole), both on a daily basis and annual basis. The model was calibrated for the period January 1, 1994 to December 31, 1997.

First, rainfall had to be was correctly divided between evapotranspiration and stream water (through lateral flow and surface runoff.) This could be achieved by adjusting the crop coefficients and canopy interception parameters. These parameters were taken from the literature (Tables 3-1 and 3-2). No adjustments were made.

Secondly, as surface runoff and base flow are the two sources of stream water, the model had to be calibrated to obtain a correct balance between surface runoff and base flow. The statistic that was used is the average annual base flow index (BFI), the ratio of base flow to total stream water. A target value of 0.81 was used, which is higher than the long-term average for the Ovejas River (0.77) because the years 1994-1997 were drier than average. Changes in BFI were obtained by adjusting the runoff curve numbers. Higher curve numbers resulted in lower BFI. The selection of curve numbers for the land use types in the Cabuyal River watershed was a difficult task. Rallison and Miller (1982) stated that the curve number procedure does not work well in areas of karst topography[1], or in any areas where a large proportion of flow is subsurface or base flow, rather than direct surface runoff. The latter applies to the Cabuyal River watershed. Curve numbers are available from lookup tables (USDA-SCS, 1972), however, these values are based on many years of studies of rainfall-runoff relationships from small rural and relatively flat watersheds in the United States. The reported values may be invalid for the highly heterogeneous landscape that is characteristic for the steep hill slopes in the Cabuyal River watershed. Moreover, the effect of slope on curve numbers is unknown, but it is likely that some limit exists to the slope for which curve

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[1] Karst is a landscape type found on carbonate rocks such as limestone, dolomite and marble. The essential characteristic of karst is the presence of a well-developed vertical and underground drainage system, general absence of surface streams, existence of springs, and the presence of small or large caves or even under ground rivers. Karst landforms are widely distributed over the earth surface, particularly in mountainous lands (Sweeting, 1973).

numbers can be used. Because of these problems, I had to select curve numbers in a crude way. An initial value of the curve number for each land use was based on USDA-SCS (1972). Land units having the same land use were assigned identical curve numbers, irrespective of differences in slopes. Adjustments in curve numbers were made per land use type, not on a land unit basis.

Thirdly, the simplified drainage and lateral flow algorithm was calibrated. Based on the Digital Elevation Model (DEM) of the watershed, the direction of water flow was computed and a stream network was delineated (see Appendix B). With these two data sets, the location and the length of the flow path from every land unit *j* to the stream ($FLOWL_j$, Eq. 2-7) could be calculated. The direction of lateral flow was assumed identical to the direction of surface flow. Next, the average slope along the flow path for each land unit *j* ($SLOPE_{AV,j}$, Eq. 2-7) was calculated for each land unit. A uniform value of 1 $md^{-1}$ was used for the hydraulic conductivity along the flow path of every land unit j ($K_{AV,j}$, Eq. 2-6) because no data was available on variation in hydraulic conductivity within the Cabuyal River watershed. ARC/INFO software was used to compute these spatially-variable parameters, which were saved as ARC/INFO grids. These three types of parameters were not changed during the calibration process. It was not possible to calibrate the simplified drainage and lateral flow algorithm for each individual hill slope because measurements of drainage out of each hill slope were not available. Instead, the model could only be calibrated for the watershed as a whole, using flow data at the watershed outlet.

Adjustments were only made to the drainage water retention factor (DRWRT, Eq. 2-27) and the storage capacity of the drainage water compartments (DRWMAX, Eq. 2-9 and 2-10). The latter had to be chosen carefully. On one hand, the storage capacity had to be sufficiently large to ensure that drainage rates would be large enough during the wet season and that drainage could be sustained over a longer period. On the other hand, the storage capacity had to be small enough to ensure that the fraction remaining drainable water would sufficiently fluctuate between its lowest value of 0 (compartments empty) and the highest value of 1 (compartments full) throughout the year. Otherwise drainage rates would not significantly differ throughout the year.

Fourthly, adjustments were made in the surface water stores retention factor, SFWRT (Eqs. 3-21 and 3-22), to control the delay in flow of surface runoff to streams. Higher SFWRT values results in higher peak flows and shorter periods of surface runoff.

Assuming that the Cabuyal River watershed and the Ovejas River watershed have similar hydrologic behavior (the former is located within the latter), adequate values of SFWRT and DRWRT were determined by visually comparing hydrograph characteristics of simulated river flow rates with those of measured flow rates of the Ovejas River and the estimated monthly flow rates for the Cabuyal River (Table 2-10). The hydrograph characteristics that were considered are runoff peak flow rates, base flow retention rate, and minimum and maximum base flows during the year. A base flow separation (Peters, 1994; Bates and Davies, 1988) can be carried out to separate the 'slow flow' component (base flow) from the 'fast flow' component (surface and sub-surface runoff). It was assumed that the slow flow component is the best approximation for the rate of drainage out of the hill slopes. De Fraiture et al. (1997) carried out a base flow separation on the daily Ovejas River flow data. Unfortunately, the years for which daily flow data were available from the Ovejas River (1974-1982 and 1994-1988) did not correspond with those that have been simulated for the Cabuyal River (1994-1997). This is the reason that only a visual inspection of hydrograph characteristics rather than comprehensive statistics analyses was applied during the calibration of the simplified drainage and lateral flow model.

Sensitivity Analysis

The purpose of a sensitivity analysis is to study the behavior of a model to different values of model parameters and input (Jones and Luyten, 1998). I analyzed the sensitivity of the SWBM model to changes in the land use (3 uniform land uses: forest, cropland and bare soil), rainfall intensity (plus and minus 20%), runoff curve numbers (plus and minus 5) and the resolution of the input data (50m and 100m grid resolution). The sensitivity analysis was carried out by making adjustments in the relevant model parameters, rerunning the simulations and comparing simulation results with reference outputs, i.e. those of the calibrated model. The simulation results that were compared include evapotranspiration, base flow index, surface runoff and river flow (averages over 4 years), and minimum and maximum base flows.

Changes in parameter values were made one at a time, keeping all other parameters at their calibrated values. The changes in rainfall intensity and curve numbers could easily be made. However, as SWBM is a distributed parameter model, changing a model parameter implies often more than just adjusting a single value. Different land use patterns and data at another resolution could only be simulated after new ARC/INFO data sets were created.

# Results and Discussion

## Calibration Results

### Parameters related to land use

For the different land use types, crop coefficients are given in Table 3-1, canopy interception parameters in Table 3-2, and rooting depths and critical fraction of plant available water in Table 3-11. All these parameters were based on the literature and lookup tables and have not been changed during the model calibration.

Table 3-11. SCS curve numbers for antecedent moisture conditions II, critical volume fraction plant available water (CFSW), and rooting depth (RD) for different land use types.

| Land Cover | CN | CFSW | RD (m) | Land Cover | CN | CFSW | RD (m) |
|---|---|---|---|---|---|---|---|
| No Vegetation | 92 | 0.90 | 0.15 | Young Woodland | 60 | 0.60 | 1.25 |
| Exposed Soil | 92 | 0.90 | 0.15 | Mature Woodland | 55 | 0.60 | 1.75 |
| Scant Pasture | 75 | 0.80 | 0.40 | Bamboo Stand | 75 | 0.60 | 1.00 |
| Dense pasture | 60 | 0.60 | 0.80 | Coffee Plantation | 70 | 0.60 | 1.00 |
| Bush Scrub | 75 | 0.60 | 1.00 | Cropped Land | 80 | 0.60 | 0.70 |

Table 3-11 gives the SCS curve numbers (CN) for the calibrated model. The average calibrated CN was 70.3 for AMC II or 52.0 for AMC I (weighted over all land use types). However, curve numbers for *bush scrub, bamboo* and *coffee plantation* were estimated because no information was available on these land use types. The curve numbers in Table 2-11 agree best to those for Hydrologic Soil Group B in the USDA-SCS tables. Soil group B has an above-average infiltration capacity and a moderately low runoff potential (USDA-SCS, 1972). Because of the generally longer flow paths in the watersheds compared to a field, part of the surface runoff may infiltrate before it reaches a stream.

Parameters related to water compartments

The calibrated surface water retention factor (SFWRT) was 0.35, i.e. on every day 35% of the water volume in the first drainage water compartment flows into the second compartment, and only 12.25% of the water inputted in the first compartment passes through both compartments and reaches a stream. The calibrated drainage water retention factor (DRWRT) was 0.0005. The maximum correction factors for flow length and soil water were $MX_{FL}$ = 1.0 (no correction for flow length) and $MX_{SW}$ =1.80, respectively. The storage capacity of every drainage water compartment (DRWMAX) was set to 2,500 $m^3$, equivalent to a drainable water depth of 0.5 m for the first and second compartments combined.

Simulated river flow

Figures 3-10 and 3-11 show the simulated and measured river flows at the outlet and in the middle of the watershed, respectively. The thicker, smoother line indicates the base flow component of the river flow. The difference between the river flow and base flow is surface runoff. Stream flow showed a fairly "flashy" behavior, i.e. high peaks and low minimum flows. This is typical for small mountainous watersheds (Black, 1996). River flow easily doubled during short periods after strong rainfall events, whereas it decreased rapidly in the dry season. There was hardly any surface runoff from June though September.

The simulated average annual river flow rates in the years 1994 through 1997 was 1019, 694, 805, and 777 L/s, respectively. The 4-year average was 824 L/s (Table 3-13). The minimum river flows at the end of the dry season (with the percentage of average annual river flow between parentheses) were 338 L/s (33%) on 7 October 1994, 295 L/s (42%) on 7 October 1995, 249 L/s (31%) on 13 October 1996, and 285 L/s (37%) on 4 November 1997. Long-term flow measurements of the Ovejas River indicated that minimum flows normally occur in late August or early September. The simulated occurrence of minimum flows of the Cabuyal River in the years 1994 through 1997 is thus later than usual. This can be explained as follows. These four years had longer than average dry periods and below average rainfall (Table 3-7). Consequently, the soil was drier than usual when the rains started. The first rains after a dry season resulted in little surface runoff and low infiltration to the deeper soil layer. This may take several weeks, depending on the intensity and frequency of the first rains, and whether the soil is dry.

The fit between the simulated and measure flows in Figures 3-10 and 3-11 is good. No explanation for the relatively large discrepancies of the measurements taken on 3 October 1994 and 30 April 1995 can be given. Rainfall or stream flows may have been measured incorrectly. It is also possible that the rainfall intensity at the weather station was much different from the rainfall intensity in other parts of the watershed. River flows changed significantly within a few days. A longer series of continuous daily flow measurements are needed for a better comparison and evaluation of the model, and calculation of a goodness-of-fit statistic.

Figure 3-12 shows the simulated river flows as a function of flow length to the watershed outlet, on a wet day in the wet season (high river flow), a dry day in the wet season (moderate river flow), and a dry day in the dry season (low river flow). A discontinuity in the stream flow indicates a location where a smaller stream merges with the Cabuyal River. The actual length of the Cabuyal River is longer than the 22.5 km shown in Figure 3-13 because the river has many small curves which can not be fully represented by a raster stream network at a resolution of 100 m.

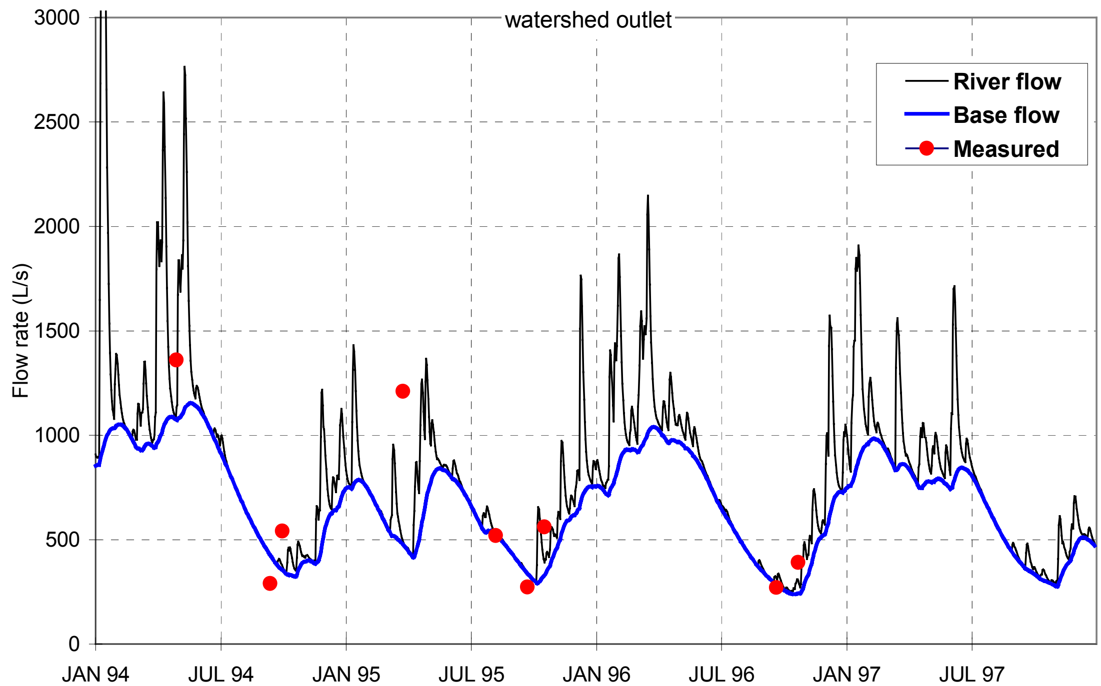



Figure 3-10. Simulated and measured river flow at the outlet of the Cabuyal River watershed.

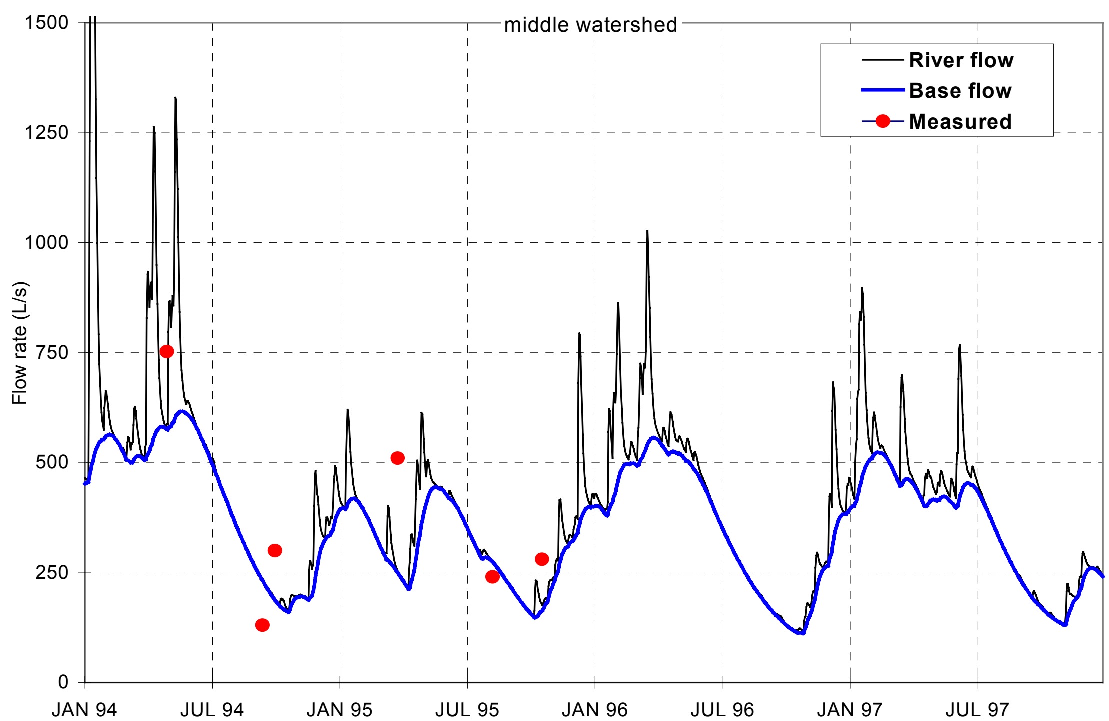



Figure 3-11. Simulated and measured river flow in the middle of the Cabuyal River watershed.

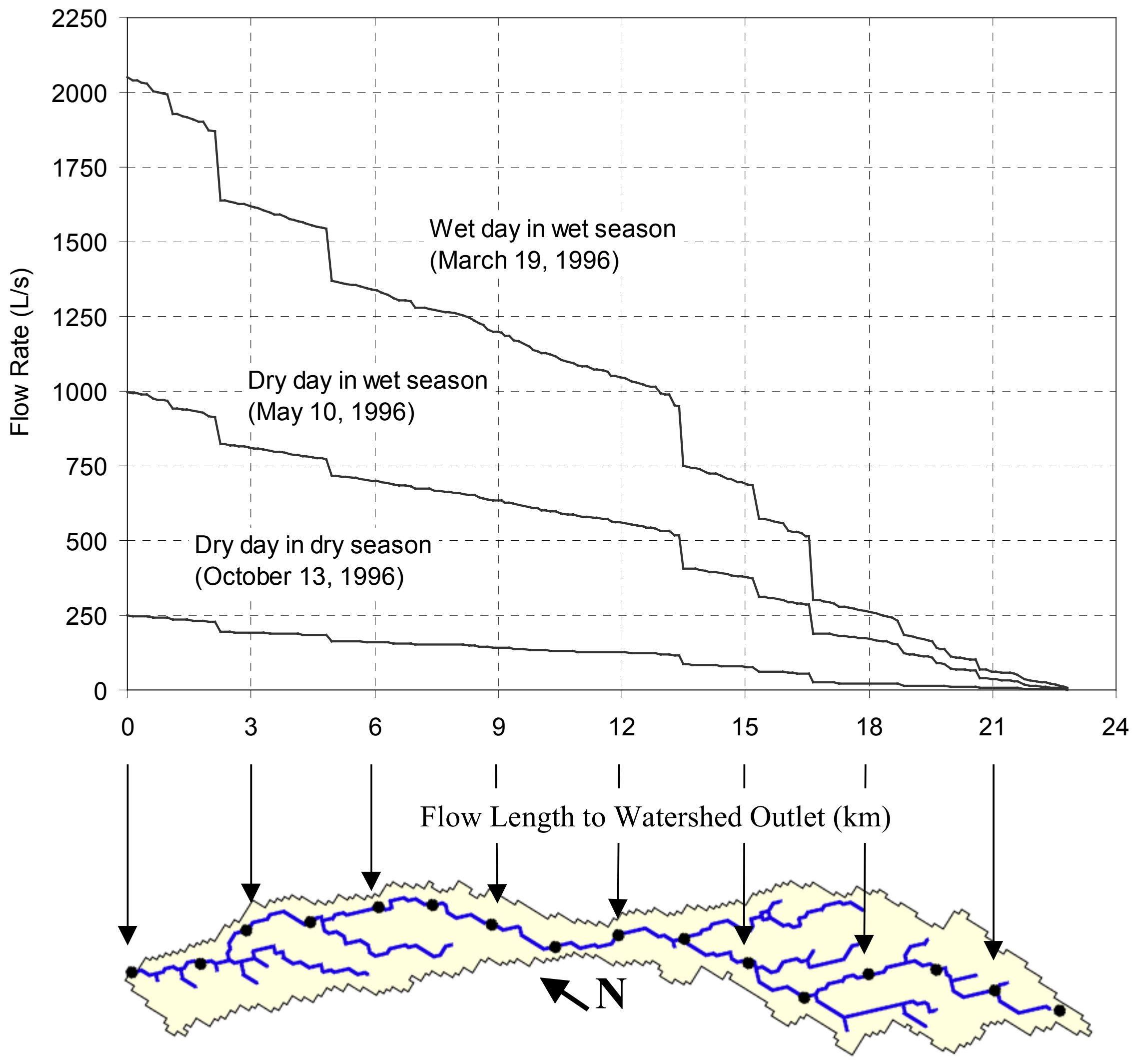



Figure 3-12. Simulated river flow (L/s) as function of flow length to the watershed outlet (km), on days with high, average, and low river flow. The watershed has been rotated 60 degrees counter clockwise to easily visualize the distances. The flow length between the small dots is exactly 1.5 km.

<u>Temporal variation in stream network</u>

The location and size of the stream network varies throughout the year. Most streams in the watershed originate at springs. Some streams may dry up during part of the year when springs run dry. Stream flow may also occur due to surface runoff. Streams will become longer and start at higher elevations if precipitation intensity increases or if rains last longer.

The SWBM model can characterize these stream dynamics. Any grid cell is considered to be a stream cell if its flow exceeds some threshold value. A threshold of 10 L/s was used to demonstrate differences in stream network for the Cabuyal River watershed. The resulting stream network compares well to streams in existing maps (not shown) and is a good reflection of the numerous small streams that can be found in the watershed.

Figure 3-13 shows the stream network at, respectively, a wet day in the wet season, a dry day in the wet season, and a dry day in the dry season (the same days for which stream flow is shown in Figure 3-12). Table 3-12 gives some statistics of these three stream networks. The location of streams, in particular their starting points, varies considerably over time. When it is drier and flow rates are low, the accumulated length of all streams and the stream density are low, and the average distance to the closest stream is high.

Table 3-12. Statistics of the stream network in the Cabuyal River watershed, on days with simulated high, average and low flow rates.

| Date | River flow (L/s) | Total length of streams (km) | Stream Density (m/ha) | Avrg. Distance to closest stream (m) |
|---|---|---|---|---|
| | | Threshold of | 10 L/s | |
| 19 MAR 96 | 2052 | 58.1 | 17.9 | 168 |
| 10 MAY 96 | 998 | 45.9 | 14.1 | 227 |
| 17 OCT 96 | 249 | 32.3 | 9.9 | 371 |
| | | Threshold of | 50 L/s | |
| 19 MAR 96 | 2052 | 35.6 | 11.0 | 310 |
| 10 MAY 96 | 998 | 28.0 | 8.6 | 441 |
| 17 OCT 96 | 249 | 16.6 | 5.1 | 1174 |

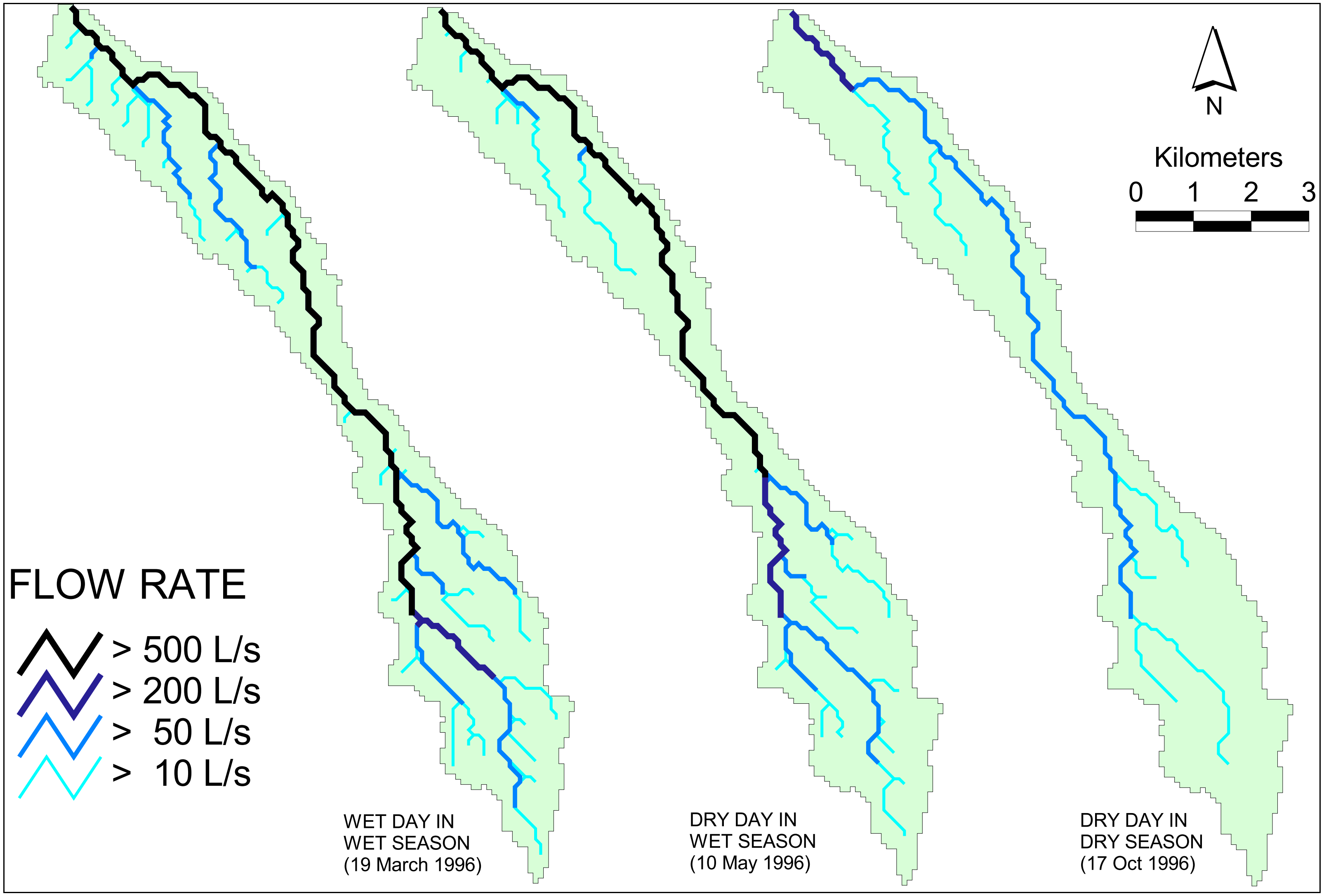



Figure 3-13. Simulated location of the streams and flow rates on three different days in 1996, Cabuyal River watershed.

<u>Spatial variation in water yield</u>

The three curves in Figure 3-12 seemed to have similar shapes. These curves were normalized by dividing all flow rates by the maximum flow rates on that particular day, that is 2052, 998 and 249 L/s, respectively. The y-value is then the fraction of the simulated total river flow at any distance from the watershed outlet. This normalization process was repeated for the flow curves of every day from January 1, 1994 to Dec 31, 1997.

Figure 3-14 shows the 5, 50, and 95 percentiles of the distribution of the flow fractions. The distribution is very narrow, indicating that the relative contribution of any part of the watershed to stream flow does not vary much over time. Where the two streams merge at a flow distance of 13.2 km from the watershed outlet, the catchment of the river is 51.2% of the watershed area. In 90% of the time, the flow fraction is between 0.455 and 0.530, with an average of 0.511. Thus, over a longer term, the upper and lower zones of the watershed contribute nearly equally to river flow.

However, the lower and upper zones vary with respect to how they contribute to river flow, i.e via surface runoff or lateral flow. The average BFI for the watershed as a whole, and averaged over all days in 1994-1997, was 0.813. It was 0.759 for the lower zone and 0.867 in upper zone. This is a considerable difference. Surface runoff contributes more to river flow in the lower zone than in the upper zone. This difference in water yield is caused by differences in land cover. Nearly all exposed soil and fallow land can be found in the lower zone and most forest can be found in the upper zone (see Table 3-4). Changes in land management can thus affect *how* the upper and lower parts of the watershed contribute to river flow.

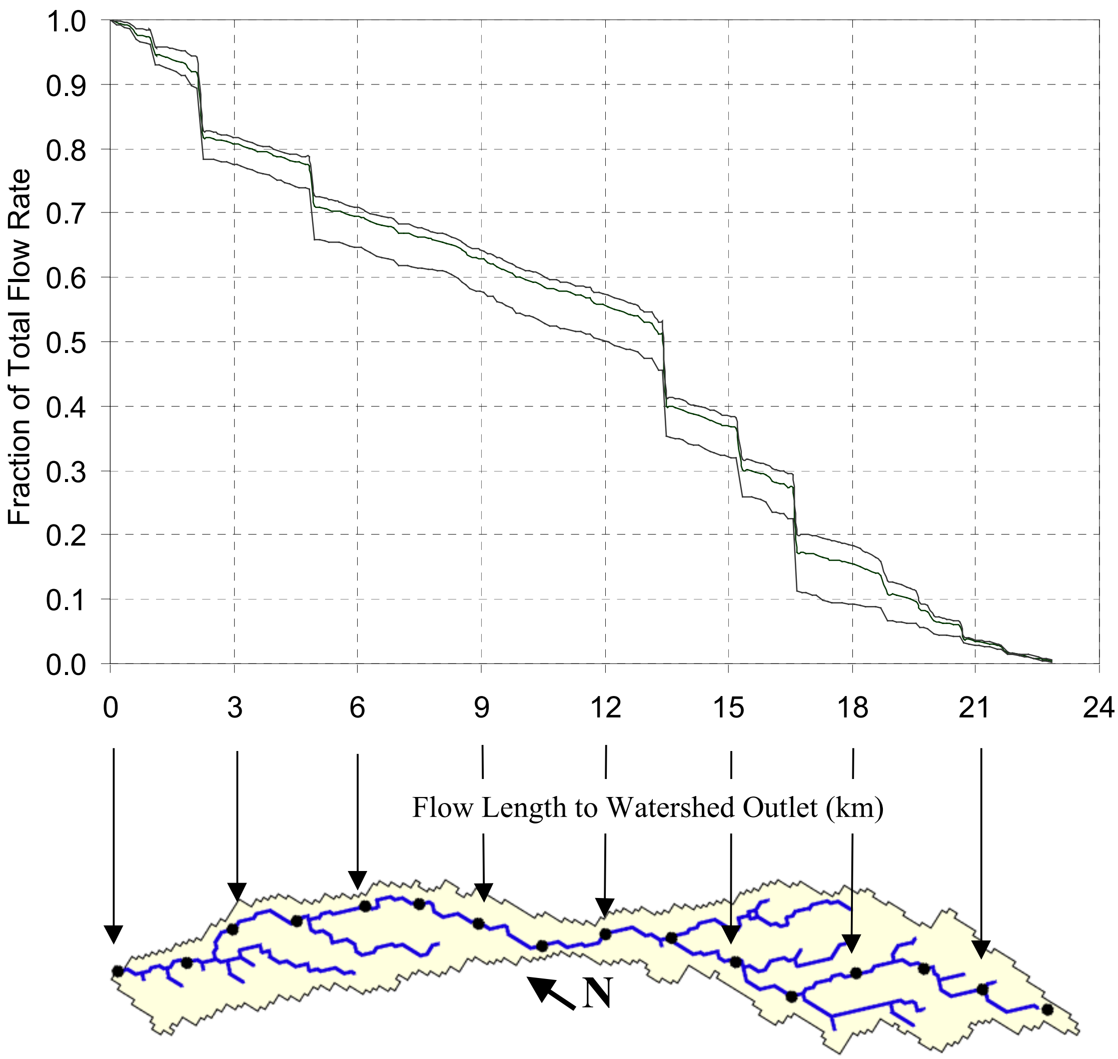



Figure 3-14. Frequency distribution (5%, 50% and 95% percentiles) of the flow rate as a fraction of the total flow rate at the watershed outlet, based on 4 years of daily simulated flow rates. The flow length between the dots is 1.5 km.

Sensitivity Analysis.

Table 3-13 summarizes specific results on simulated maximum, average and minimum water flows and evapotranspiration, and Table 3-14 gives relative sensitivities to changes in curve number and precipitation. Every different sensitivity analysis will be discussed in a separate section.

<u>Changes in land use</u>

Model sensitivity to changes in land use has been analyzed by comparing three uniform land use patterns: (1) a fully forested watershed, (2) only cropped land and (3) only bare soil. These three land use patterns are extremes, each resulting in a hydrological response that can be expected to differ considerably from the other land use types. Forest has a dense canopy with mulch and litter on the soil surface that can intercept and infiltrate relatively more rain. Bare soil, on the other hand, is highly susceptible to surface runoff. Cropped land is assumed to be a mixture of different crops in different stages of development, possibly with some fallow plots. It is unlikely that any single land use type will ever characterize the entire watershed. However, results of the sensitivity analyses explain model behavior for such land use changes. Model parameters for *forest* are the averages of the parameters for *Young Woodland* and *Mature Woodland* in Tables 3-1, 3-2 and 3-11. Parameter values for *Bare Soil* and *Cropped Land* were taken from these tables.

Figure 3-15 presents the simulated stream flow with uniform cropped land. Cropped land resulted in relatively minor changes in the hydrological response of the watershed (Figure 3-10). The average base flow index (BFI) and surface runoff remained nearly unchanged (Table 3-13). Evapotranspiration was 4.6% lower and, consequently, the water yield of the watershed increased nearly 5%.

The uniform forest cover gave very different simulation results (Figure 3-16). Annual ET increased about 13%. This was caused by the forest's ability to intercept rain and to extract water from deeper soil. Because of the increase in ET, less water was left for surface runoff and base flow. Average river flow decreased from 824 to 705 L/s and base flow lowered from 238 to 184 L/s (Table 3-13). Surface runoff decreased from 154 to 90 L/s.

Thus, forest decreased total water yield relative to land use of the base case. Calder (1988) and Hamilton (1985) note that it is often incorrectly thought that forests increase water yield.

A bare soil cover had opposite effects on watershed hydrology (Figure 3-17). ET was reduced from 917 to 504 L/s and average river flow increased from 824 to 1226 L/s (Table 3-13) River flow showed a erratic behavior with high peaks caused by more frequent and heavy surface runoff. The base flow index was lower (0.612 vs. 0.862), indicating that the relative contribution of surface runoff to river flow increased.

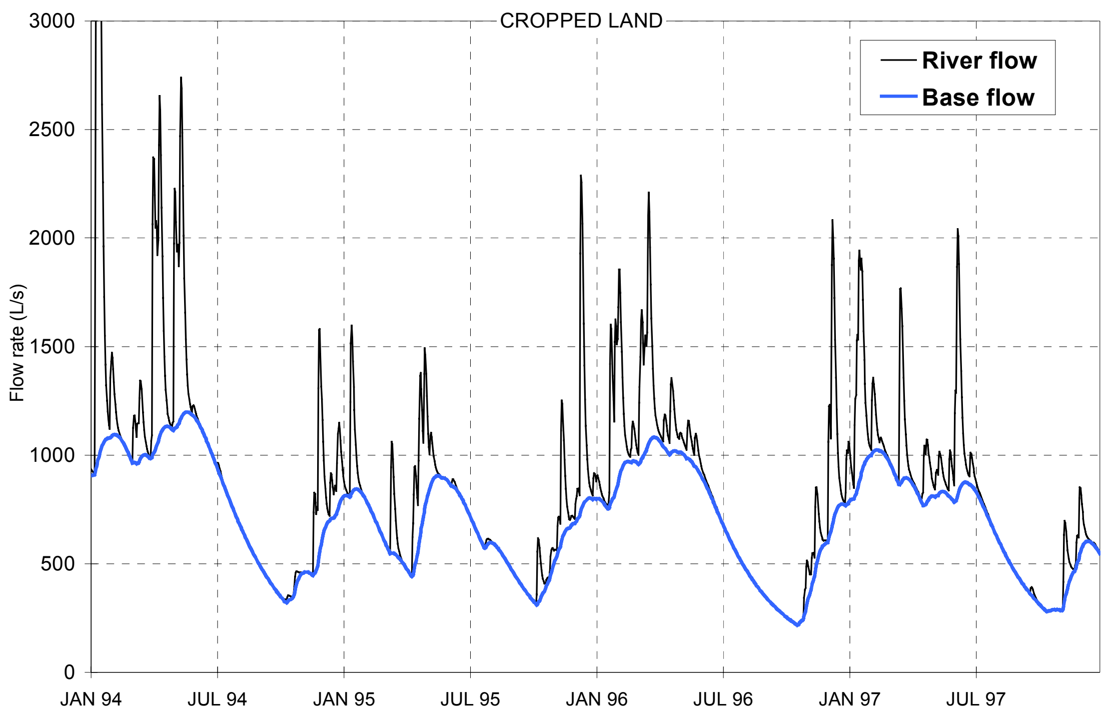



Figure 3-15. Simulated river flow at the watershed outlet with only cropped land.

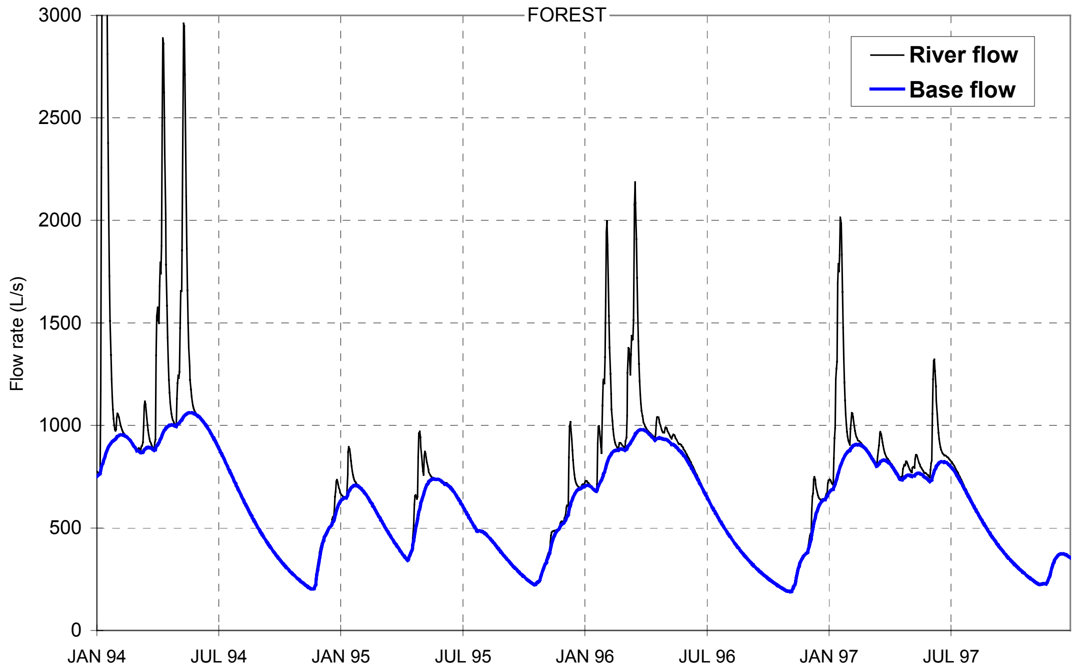



Figure 3-16. Simulated river flow at the watershed outlet with only forest cover.

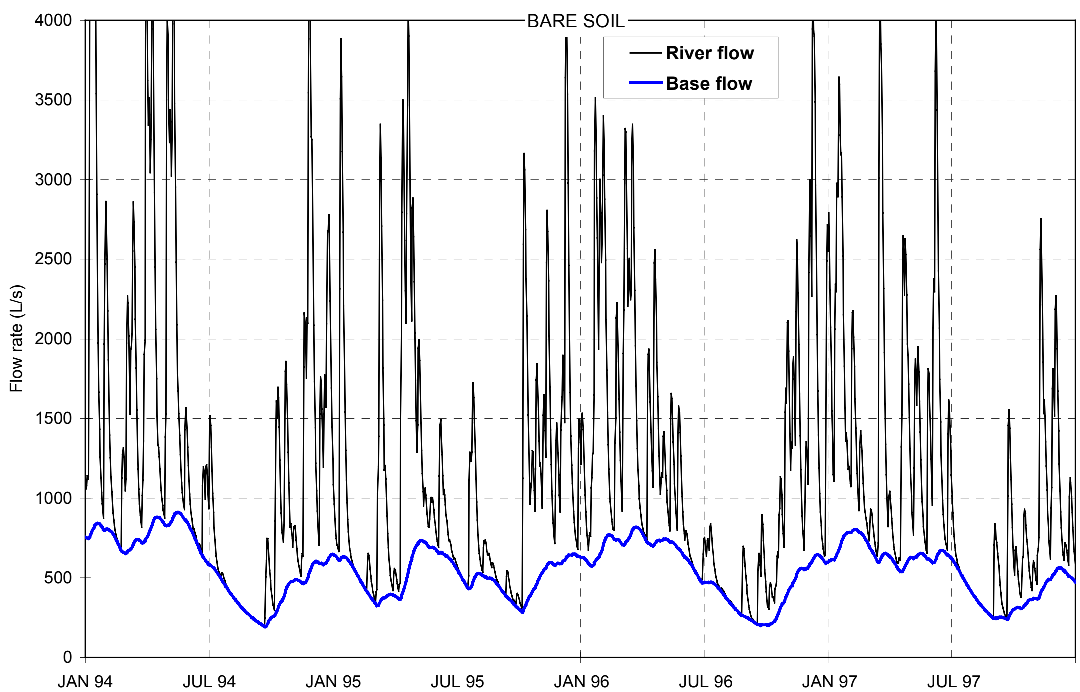



Figure 3-17. Simulated river flow at the watershed outlet with only bare soil.

Table 3-13. Results of sensitivity analysis, based on simulation of the years 1994-1997. Values of important model variables for changes in data resolution, land use, curve numbers, and rain intensity. The shaded row applies to the calibrated model.

| Sensitivity case | grid size (m) | Avrg. ET ($mm\ yr^{-1}$) | ET/Rain (-) | BFI (-) | Minimum Base flow | Maximum Base flow | Average Base flow | Average Runoff | Average River flow |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | ---------------- | ---------------- | L/s | ---------------- | ---------------- |
| CALIBRATED | 100 | 917 | 0.541 | 0.813 | 238 | 1153 | 670 | 154 | 824 |
| Smaller grid cell | 50 | 906 | 0.534 | 0.803 | 234 | 1161 | 672 | 165 | 837 |
| Cropped land | 100 | 874 | 0.516 | 0.818 | 217 | 1198 | 707 | 157 | 865 |
| Dense Forest | 100 | 1038 | 0.612 | 0.872 | 189 | 1061 | 615 | 90 | 705 |
| Bare Soil | 100 | 504 | 0.297 | 0.444 | 191 | 909 | 544 | 682 | 1226 |
| CN 5 lower | 100 | 917 | 0.541 | 0.846 | 254 | 1185 | 697 | 127 | 824 |
| CN 5 higher | 100 | 915 | 0.540 | 0.720 | 195 | 1051 | 594 | 231 | 825 |
| 20% less rain | 100 | 877 | 0.647 | 0.868 | 141 | 923 | 449 | 68 | 517 |
| 20% more rain | 100 | 939 | 0.462 | 0.737 | 329 | 1257 | 842 | 300 | 1142 |

Table 3-14. Average relative sensitivity[1] of important model variables to changes in runoff curve numbers and precipitation intensity, calculated from data in Table 3-13.

| | Average ET | ET/Rain | Average BFI | Min. BF | Max. BF | Average BF | Runoff | River flow |
|---|---|---|---|---|---|---|---|---|
| Curve Number | -0.015 | -0.013 | -1.090 | -1.743 | -0.817 | -1.081 | 4.748 | 0.009 |
| Precipitation | 0.169 | -0.855 | -0.403 | 1.975 | 0.724 | 1.466 | 3.766 | 1.896 |

[1] The relative sensitivity was calculated as: $((\Delta Y_2-\Delta Y_1)/Y)/((\Delta X_2-\Delta X_1)/X))$. The base value of the curve number is 70.3. The average relative sensitivity of *Minimum BF* to the *Curve Number*, for example, is calculated as ((195-254)/238)/((5+5)/70.3) = -1.743.

Changes in curve numbers

The curve number is generally considered to be one of the most important and sensitive parameters in hydrological models (e.g. Bosch et al., 1998). I analyzed the impact of an increase and decrease in all curve numbers by 5 units simultaneously. The curve numbers for each land use type are given in Table 3-15.

Table 3-15. Normal, 5 lower and 5 higher curve numbers, for Antecedent Moisture Conditions (AMC) I and II, as used in the sensitivity analysis.

| Land Cover | -5 | normal | +5 | -5 | normal | +5 |
|---|---|---|---|---|---|---|
| | | AMC=II | | | AMC=I | |
| No Vegetation | 88.0 | 93.0 | 98.0 | 82.7 | 89.7 | 97.0 |
| Exposed Soil | 88.0 | 93.0 | 98.0 | 82.7 | 89.7 | 97.0 |
| Scant Pasture | 70.0 | 75.0 | 80.0 | 59.5 | 65.6 | 72.0 |
| Dense pasture | 55.0 | 60.0 | 65.0 | 42.6 | 48.0 | 53.6 |
| Bush Scrub | 70.0 | 75.0 | 80.0 | 59.5 | 65.6 | 72.0 |
| Young Woodland | 65.0 | 60.0 | 65.0 | 42.6 | 48.0 | 53.6 |
| Mature Woodland | 50.0 | 55.0 | 60.0 | 37.5 | 42.6 | 48.0 |
| Bamboo Stand | 70.0 | 75.0 | 80.0 | 59.5 | 65.6 | 72.0 |
| Coffee Plantation | 65.0 | 70.0 | 75.0 | 53.6 | 59.5 | 65.6 |
| Cropped Land | 75.0 | 80.0 | 85.0 | 65.6 | 72.0 | 78.6 |
| WEIGHTED AVERAGE | 65.3 | 70.3 | 75.3 | 46.1 | 52.0 | 58.6 |

Figures 3-18 and 3-19 show the simulated river flows for the lower and higher curve numbers, respectively. Changes in the curve number had the greatest effect on the average surface runoff. Surface runoff increased from 154 to 231 L/s for the higher curve numbers whereas it decreased to 127 L/s for the lower curve numbers (Table 3-13). An opposite effect was observed on the minimum, average and maximum base flow and the BFI. The BFI increased from 0.813 to 0.846 for the lower curve numbers, whereas it decreased to 0.720 for the higher curve numbers. The minimum and maximum base flows were more sensitive to an increase in curve numbers (change of -13.1% and -8.9%, respectively) than to a decrease in curve numbers (+6.7% and +2.8%, respectively) (Table 3-13). Minimum base flows are more sensitive to changes in curve numbers than maximum base flows (Table 3-14) Evapotranspiration and average river flow were not affected by changes in the curve numbers.

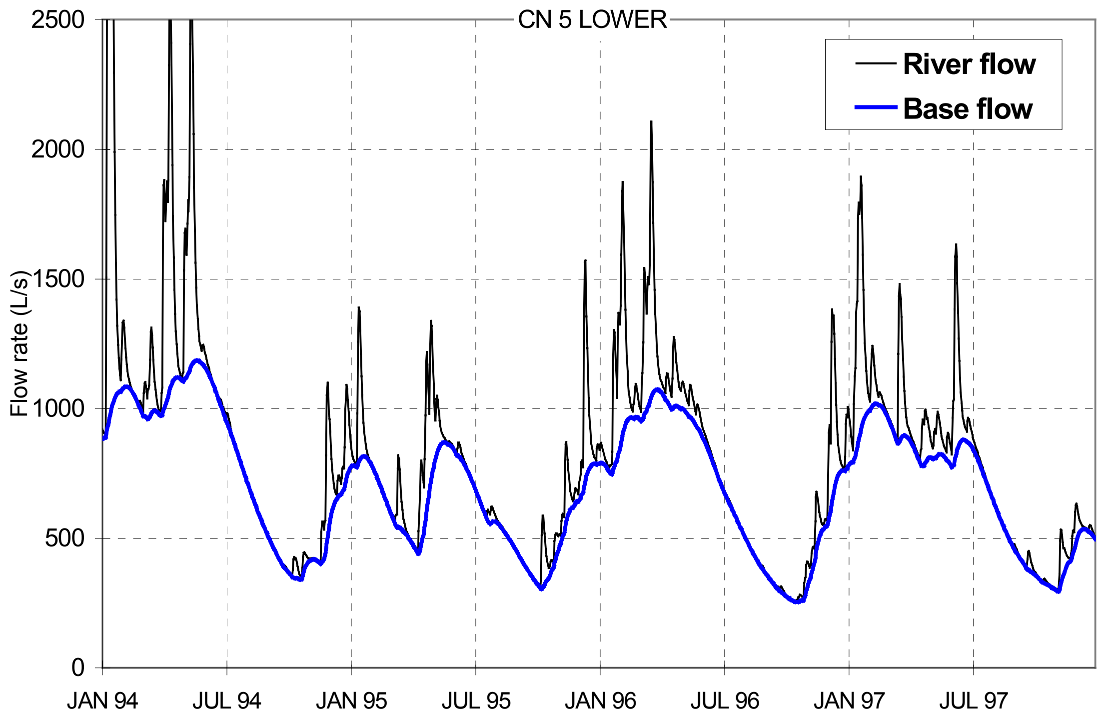



Figure 3-18. Simulated river flow at the watershed outlet with lower curve numbers.

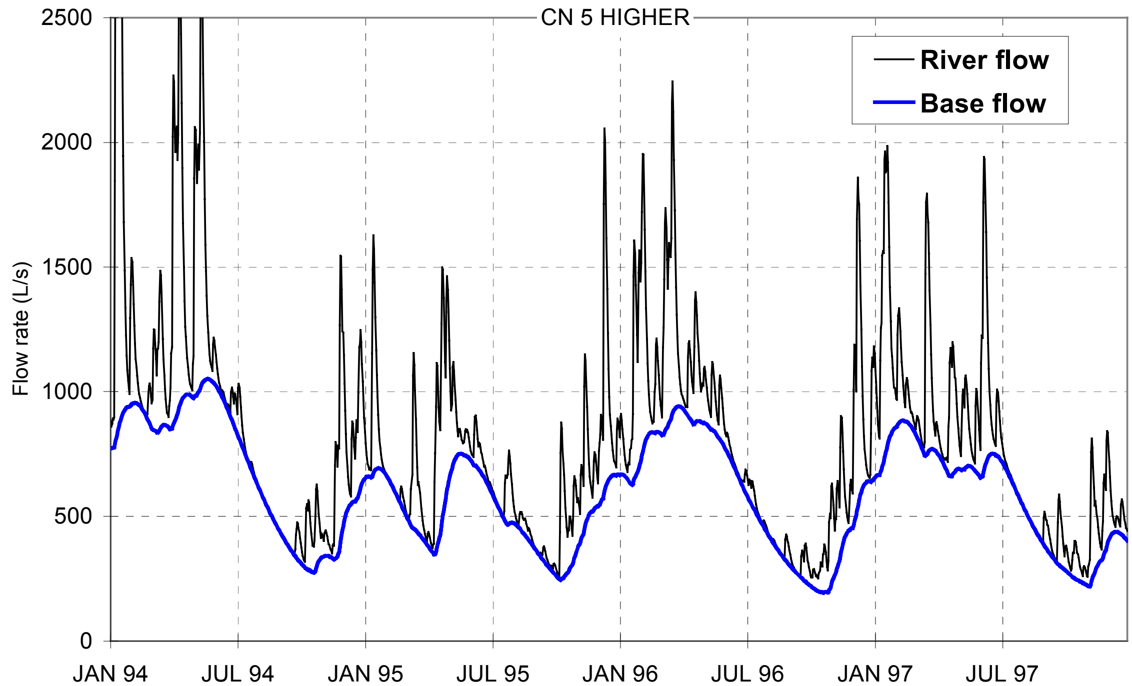



Figure 3-19. Simulated river flow at the watershed outlet with higher curve numbers.

Change in data resolution

Any change in the resolution of the DEM implies a change in the representation of the topology. Consequently, slight changes can be expected in all landscape characteristics that are derived from the DEM, such as slopes, boundaries of the watershed, locations of streams and the total area of the watershed. Although neither the model nor the ArcView GIS software put any restrictions on the size of a grid cell and the maximum number of cells in a grid, these settings should be carefully considered based on the total area of the watershed, resolution of the input data and desired accuracy. A grid cell should be sufficiently small to avoid loss of too much information through aggregation. However, a large number of grid cells will considerably decrease execution speed.

Byne (1996) found that a DEM with a resolution of 25 to 50 m minimized the error in the DEM for the steep hillsides like the Cabuyal River watershed. The optimal cell resolution is not necessarily 'the smaller the better'. I found that watershed boundaries and the stream network could adequately be derived from a DEM of 100 m resolution. For a DEM resolution of 10, 25, 50 and 100 m, the area of the DEM-delineated watershed was 3,271 ha, 3,268, 3,253 and 3,246 ha, respectively. The negative correlation between watershed area and cell size is coincidence. Figure 3-20 presents the watershed boundaries and location of streams as delineated from DEMs of 50 m and 100 m resolution. They coincide very well, except for two minor discrepancies in the watershed boundaries in the south.

Changes in grid resolution also imply that the area covered by each land use type changes. Figure 3-21 shows part of the land use grid at the original 10 m resolution. This data set has been resampled to a 50 m grid (Figure 3-22) and 100 m grid (Figure 3-23) using a maximum area criterion, i.e. the most frequent land use type is assigned to the aggregated grid cell. Table 3-16 gives the areas covered by land use type and the change in those areas caused by aggregation of land use data. Aggregation of land use caused an overrepresentation of pasture and bush scrub. The areas without vegetation, young woodland, bamboo, coffee and cropped land were significantly reduced. In general, the effect of aggregating was that land use types that are dominant become more dominant and those that are scarce more scarce. The aggregation error was largest for resampling from 10 to 100 m.

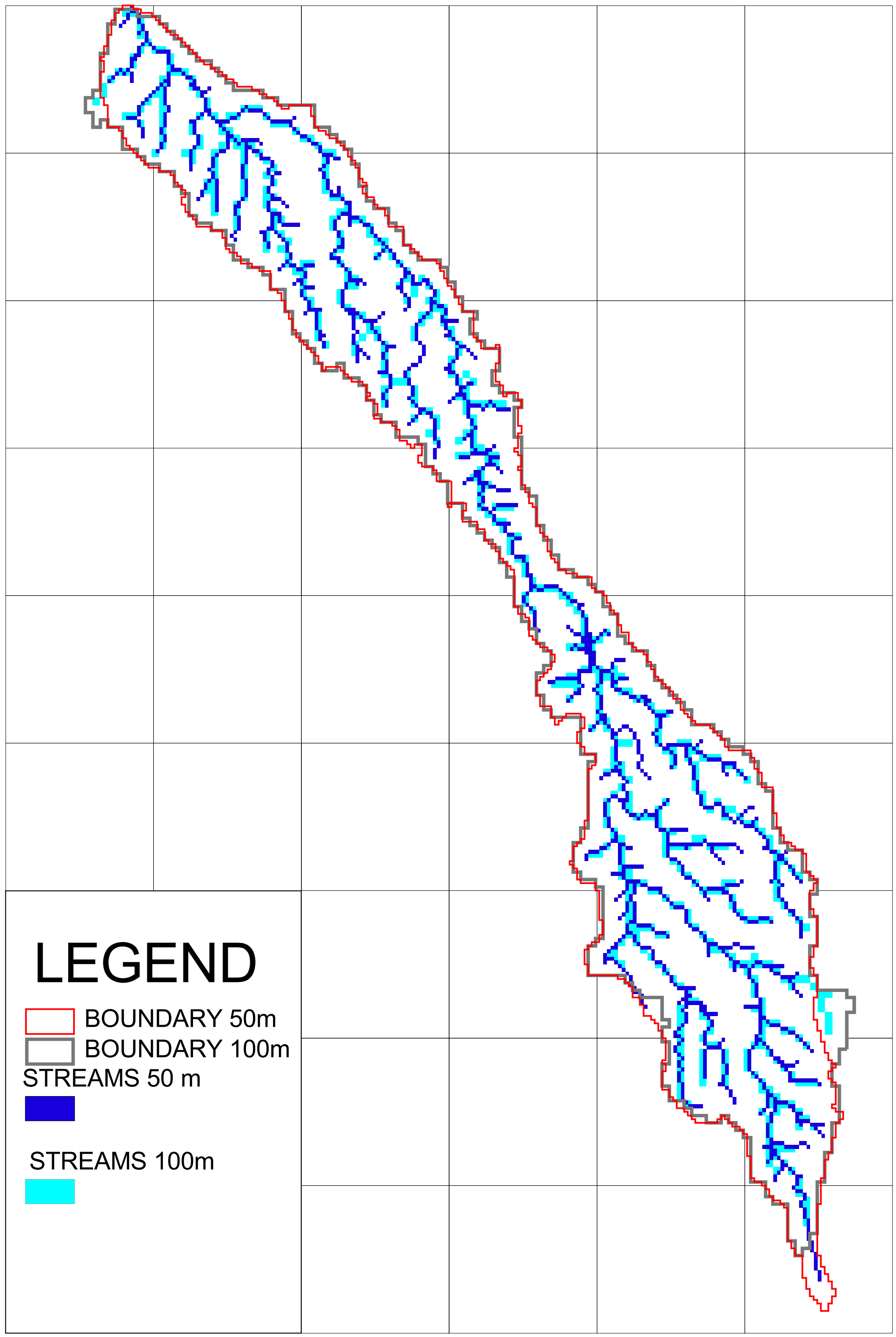


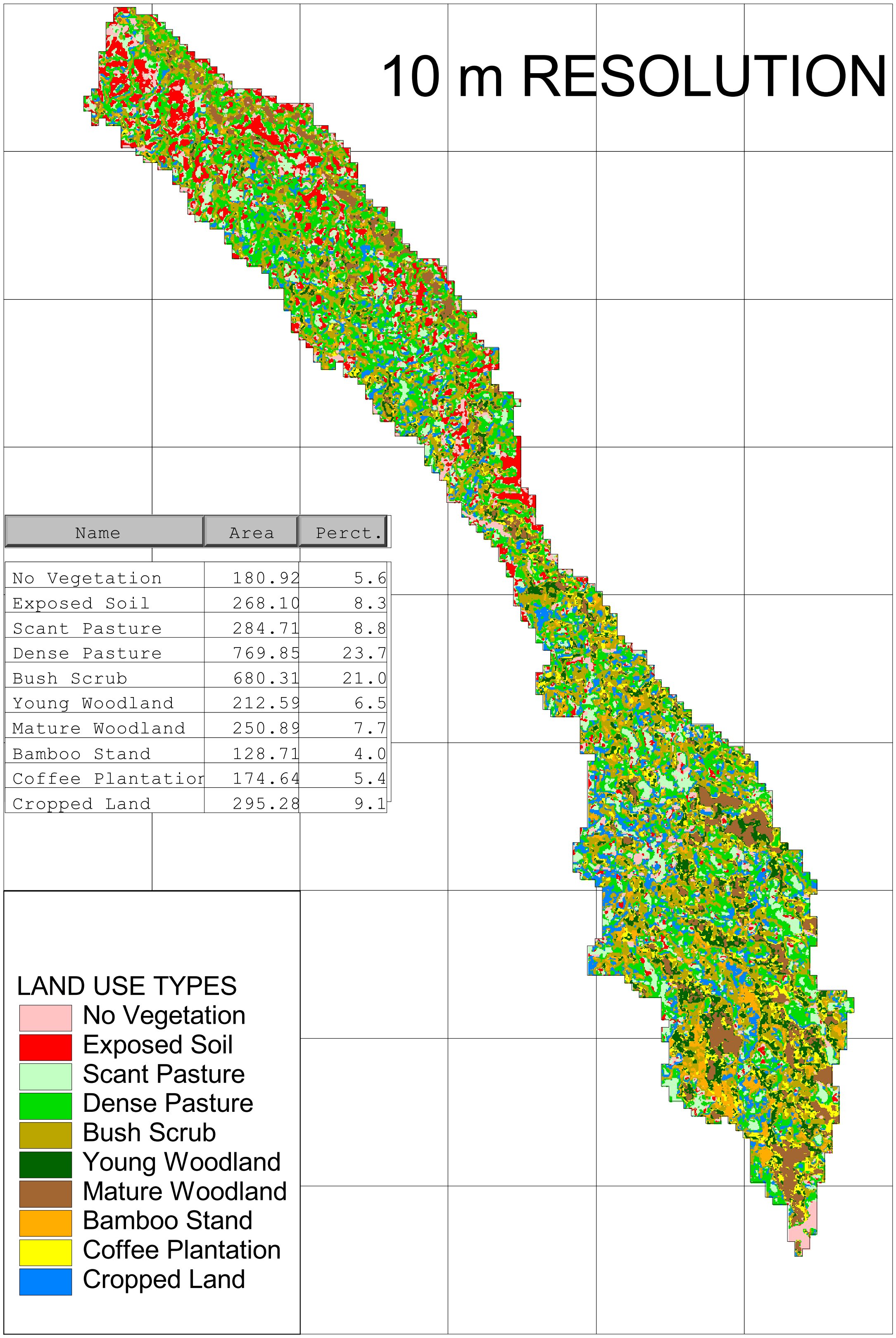

Figure 3-20. Watershed boundaries and streams as delineated from a 50m and 100m resolution DEM. Streams are delineated based on a minimal contributing area of 6 ha.

Table 3-16. Areas (in ha) by land use type in the Cabuyal watershed, at 10m, 50m and 100m resolution, and relative change due to aggregation of the original 10 m data.

| Land use type | Area (ha) 10 m res. | Area (ha) 50 m res. | Area (ha) 100m grid | Perct. chg. 50 m res. | Perct. chg. 100 m res. |
|---|---|---|---|---|---|
| No Vegetation | 180.92 | 156.25 | 126.00 | -13.64 | -30.36 |
| Exposed Soil | 268.10 | 265.25 | 267.00 | -1.06 | -0.41 |
| Scant Pasture | 284.71 | 260.50 | 231.00 | -8.50 | -18.86 |
| Dense Pasture | 769.85 | 839.00 | 1012.00 | 8.98 | 31.45 |
| Bush Scrub | 680.31 | 759.00 | 797.00 | 11.57 | 17.15 |
| Young Woodland | 212.59 | 199.00 | 179.00 | -6.39 | -15.80 |
| Mature Woodland | 250.89 | 263.00 | 260.00 | 4.83 | 3.63 |
| Bamboo Stand | 128.71 | 109.25 | 81.00 | -15.12 | -37.07 |
| Coffee Plantation | 174.64 | 133.75 | 83.00 | -23.41 | -52.47 |
| Cropped Land | 295.28 | 261.00 | 210.00 | -11.61 | -28.88 |
| Total | 3246 | 3246 | 3246 | n/a | n/a |

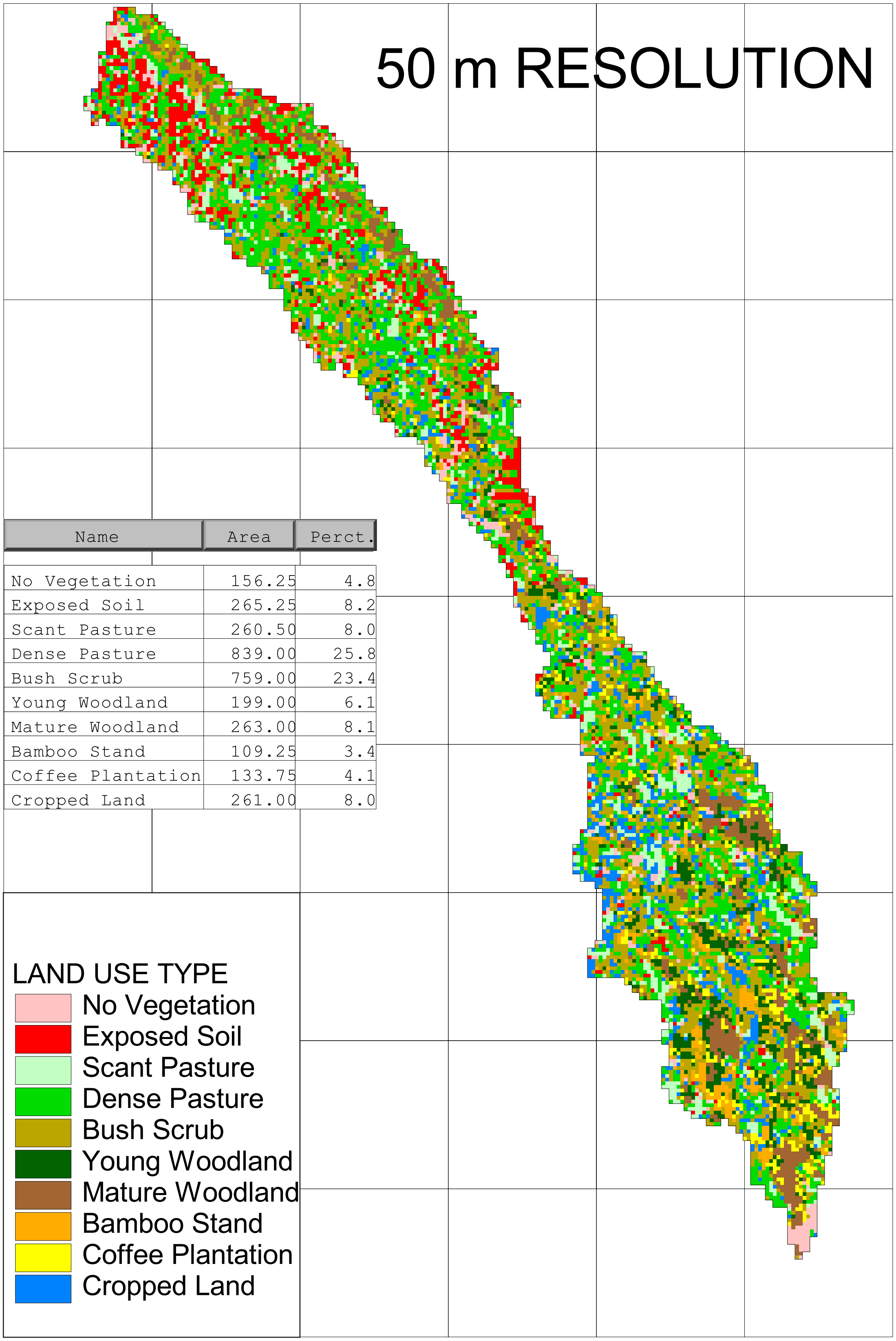
A simulation was carried out using the 50 m land use grid and DEM. Simulation results were compared to those of the calibrated model (first two rows in Table 3-13). The changes in simulated flow rates are relatively small. Surface runoff increased from 154 to 165 L/s and average river flow from 824 to 837 L/s, and ET decreased by 1.2% to 906 mm $yr^{-1}$. The minimum, average and maximum base flows hardly changed.

These numbers are not typical and cannot be generalized. The effects may be different with other land use data, or in another watershed where topography is different. Any change in the resolution of the input data requires an analysis of the impact of this change on model behavior. It may also require calibration of the model for the new spatial resolution.



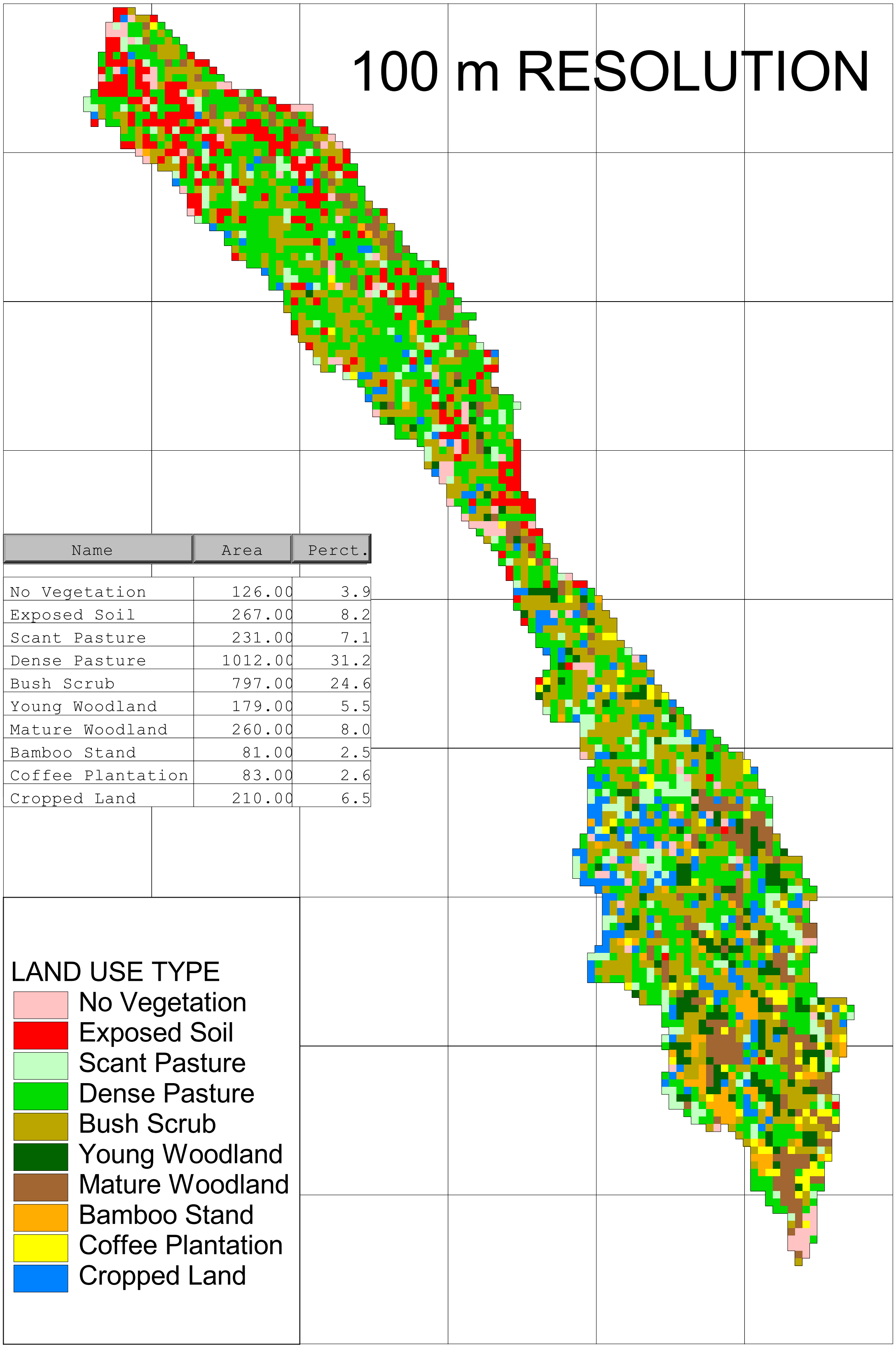

| Name | Area | Perct. |
|---|---|---|
| No Vegetation | 180.92 | 5.6 |
| Exposed Soil | 268.10 | 8.3 |
| Scant Pasture | 284.71 | 8.8 |
| Dense Pasture | 769.85 | 23.7 |
| Bush Scrub | 680.31 | 21.0 |
| Young Woodland | 212.59 | 6.5 |
| Mature Woodland | 250.89 | 7.7 |
| Bamboo Stand | 128.71 | 4.0 |
| Coffee Plantatior | 174.64 | 5.4 |
| Cropped Land | 295.28 | 9.1 |

Figure 3-21. Land use in the Cabuyal River watershed at 10 m resolution (original).




| Name | Area | Perct. |
|---|---|---|
| No Vegetation | 156.25 | 4.8 |
| Exposed Soil | 265.25 | 8.2 |
| Scant Pasture | 260.50 | 8.0 |
| Dense Pasture | 839.00 | 25.8 |
| Bush Scrub | 759.00 | 23.4 |
| Young Woodland | 199.00 | 6.1 |
| Mature Woodland | 263.00 | 8.1 |
| Bamboo Stand | 109.25 | 3.4 |
| Coffee Plantation | 133.75 | 4.1 |
| Cropped Land | 261.00 | 8.0 |

Figure 3-22. Land use in the Cabuyal River watershed, resampled at 50 m resolution.




| Name | Area | Perct. |
|---|---|---|
| No Vegetation | 126.00 | 3.9 |
| Exposed Soil | 267.00 | 8.2 |
| Scant Pasture | 231.00 | 7.1 |
| Dense Pasture | 1012.00 | 31.2 |
| Bush Scrub | 797.00 | 24.6 |
| Young Woodland | 179.00 | 5.5 |
| Mature Woodland | 260.00 | 8.0 |
| Bamboo Stand | 81.00 | 2.5 |
| Coffee Plantation | 83.00 | 2.6 |
| Cropped Land | 210.00 | 6.5 |

Figure 3-23. Land use in the Cabuyal River watershed, resampled at 100 m resolution.

Changes in precipitation

Changes in precipitation have a direct impact on watershed hydrology and water yields. I analyzed the impact of a 20% decrease and a 20% increase in precipitation. The 20% change in precipitation corresponds to 184 mm $yr^{-1}$. The number of rainy days and their distribution in time remained the same as in all other simulations. Figures 3-24 and 3-25 show the simulated river flow for the situation with 20% less and 20% more precipitation, respectively. Table 3-14 shows that surface runoff was most sensitive to changes in precipitation and ET was least sensitive. With 20% less precipitation, average surface runoff drops from 154 to 68 L/s and river flow from 824 to 517 l/s. The BFI became as high as 0.868. With 20% more precipitation, average river flow increased to 1142 l/s and the BFI became 0.737. The difference in surface runoff and BFI is obvious from comparison of Figures 3-24 and 3-25. The changes in ET were only –4.3% +2.4%, respectively.

Average precipitation from 1994 to 1997 was 17.8% lower than the long-term average annual rainfall in the region (1697 vs 2066 mm $yr^{-1}$, see Tables 2-6 and 2-7). Adding 20% to the 1994-1997 precipitation data resulted in an average precipitation of 2036 mm $yr^{-1}$, close the long term average. Hence the simulation results with the 20% higher precipitation may better describe the "average" situation for the Cabuyal River than the simulation results obtained with the actual 1994-1997 weather data.

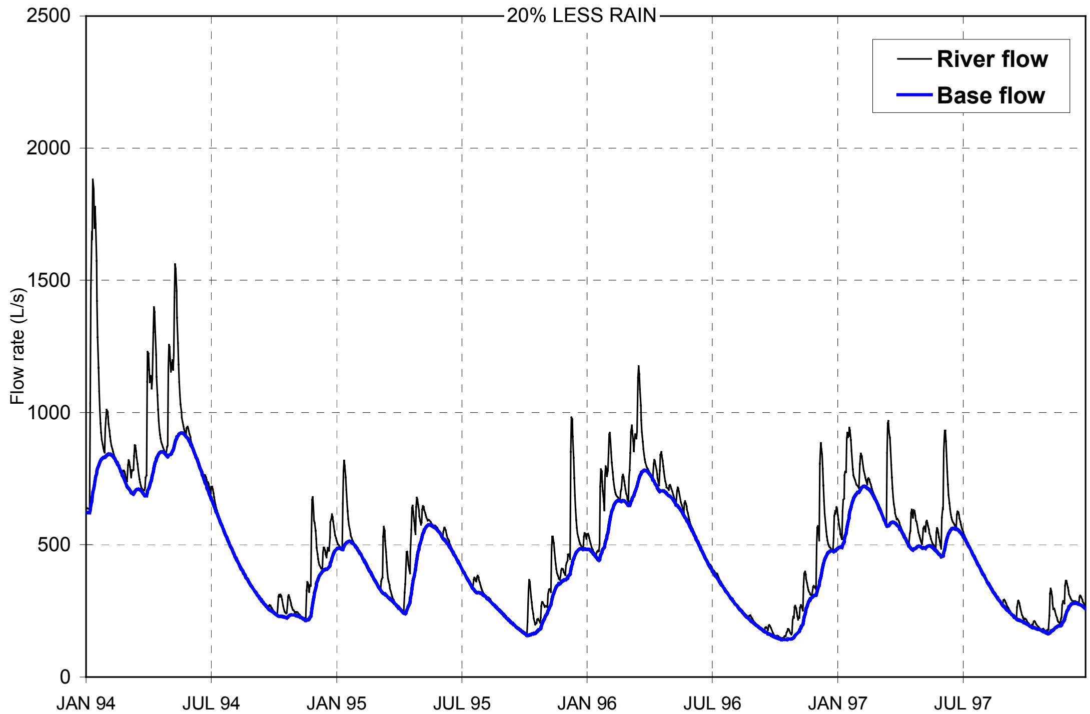



Figure 3-24. Simulated river flow at the watershed outlet with 20% lower precipitation.

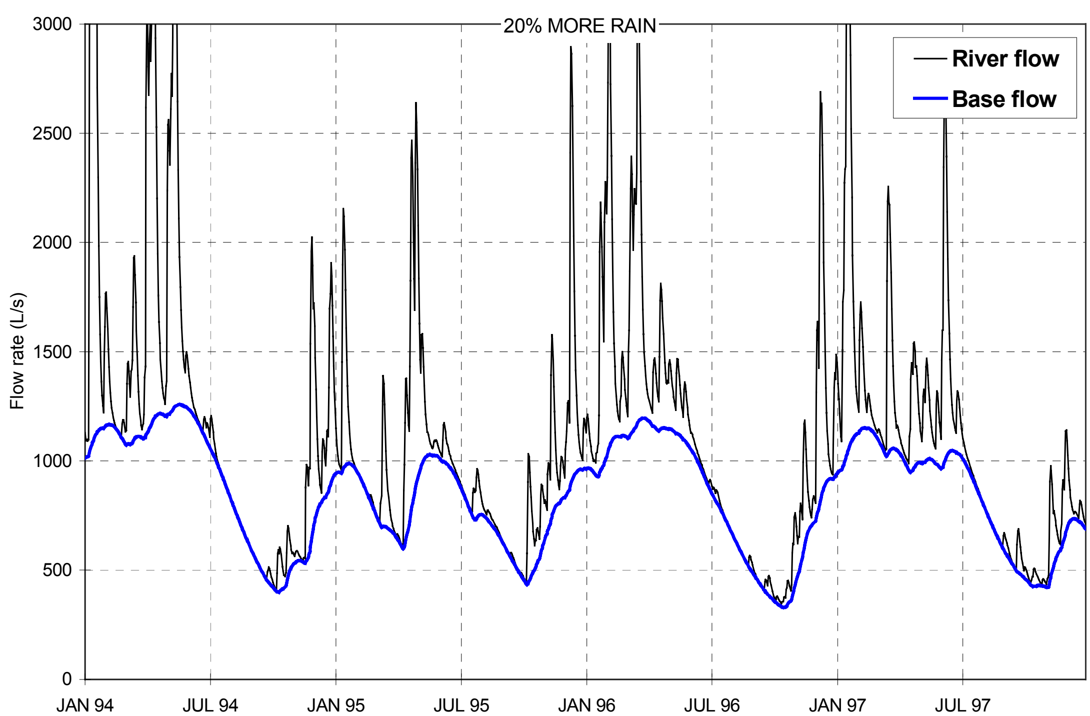



Figure 3-25. Simulated river flow at the watershed outlet with 20% higher precipitation.

## Conclusions

Most parts of SWBM were based on existing, empirical relationships on hydrological processes in the canopy and the soil, except for the flow of surface runoff and lateral flow from land units to streams. These two processes were modeled using a 2-compartment distributed delay, which provided a good representation of these flows. SWBM was a tradeoff between hydrological detail and usefulness for assessing water scarcity on a watershed scale and identifying critical "break points" in watershed behavior. The functionality and capabilities of SWBM are distinctly different from those of many other hydrological models, in particular because (1) streams are the core feature of the model, (2) water use from streams and storage in dams can be simulated, and (3) the model is GIS-embedded and makes use of GIS raster structures for all computations.

Absence of any long-term, daily flow data of the Cabuyal River was thought to be a main problem during the calibration of the model for the Cabuyal River watershed. However, by assuming that the hydrological behavior of the Cabuyal River and the Ovejas River watersheds were similar, daily flow data of the latter were successfully used for calibration of the model, in particular for calibration of surface runoff and lateral flow characteristics. Simulated flows of the Cabuyal River were realistic and close to the few available flow measurements. Simulated flows of the Cabuyal River changed significantly over space and time during the years 1994 through 1997. Minimum river flow rates at the end of dry seasons in those years were between 31% and 42% of the average annual river flow rates, whereas flow rates more than doubled during strong rainfall events due to surface runoff.

In contrast to what is thought by some local farmers, the lower and upper parts of the watershed contributed equally to stream water. However, the difference in base flow indices of the lower and upper parts, respectively 0.759 and 0.867, indicated a significant difference in *how* they contributed to stream water (surface runoff or base flow). This difference may have important implications for land management. For example, land management practices that reduce soil erosion and reduce peak flow rates would be most useful in the lower part.

Changes in the resolution of the DEM and land use data changed the representation of the landscape (in particular the distribution of land use) and affected simulation outcomes. Therefore, the model should be recalibrated after any such changes in data occur. The model showed that the hydrological response of watersheds with uniform forest, uniform cropped land and uniform bare soil were very different. A bare soil resulted in high annual surface runoff and river flow, whereas and a forest land cover gave low annual surface runoff and river flow. Thus, changes in land use may result in considerable changes in water availability over space and time. The model was very sensitive to changes in runoff curve numbers and precipitation. These changes not only affected the estimated river flow rate, but also changed the relative contributions of surface runoff and base flow to river flow.

# CHAPTER 4
# SIMULATING WATER USE AND DAMS IN THE CABUYAL RIVER WATERSHED

## Introduction

The streams in the Cabuyal River watershed in southwest Colombia are very important to the local communities because stream water is used to serve domestic, industrial and agricultural water needs. The results in Chapter 3 showed that the flow rate of the Cabuyal River strongly varies over space and time. The simulated average annual flow rate at the watershed outlet was 824 L/s, but it more than doubled during and immediately after strong rainfall events, whereas it decreased below 250 L/s during the dry season.

Competition for water and conflicts about water use has increased during the last decades (de Fraiture et al., 1997; Ravnborg and Ashby, 1996). Reduced or insufficient water availability during the dry season was recognized as a serious problem (CIAT, 1993). Water extraction for streams has always been virtually unregulated, potentially allowing farmers and industries to extract large volumes of water. Some farmers built dams in the river to collect irrigation water and refill small ponds. These practices may reduce water availability in downstream communities to levels below the water demand. Most water problems occurred in the middle and lower parts of the watershed. Although downstream communities have the advantage of benefiting from a larger catchment area and thus higher stream flow, they also experience the greatest effects of any changes in land and water use that occur at higher elevations.

Experience with stakeholders and decision making processes in the watershed showed that it is increasingly important to provide quantitative information about how water availability changes over space and time as changes in the landscape and water use occur (CIAT, 1997). It is particularly important to show the impact of water extraction and construction of dams on water availability, and any associated upstream-downstream affects. Local stakeholders and decision-makers are not very aware of the interdependencies between land and water resources, the impact of using them, ad any associated upstream-downstream effects. Providing this information is considered a critical part in negotiating compromises to resolve conflicts, gaining commitment of local stakeholders to institutional arrangements and resource preserving management practices, and helping decision-makers guide development in a direction that is desirable for the local communities and their people (Knapp et al., 1999).

This information is also of interest within a larger regional context. The Cabuyal River watershed is a representative watershed for the hillsides agro-ecosystem in the Cauca department in Colombia. The Cauca Valley Corporation developed plans to divert water from the larger Ovejas River—to which the Cabuyal River is a tributary—to the Sajvajina dam to benefit a hydropower plant (Estrada, 1993). Any changes in water availability in the Cabuyal River would thus affect the water supply to this plant. These effects are marginal in absolute terms because the Cabuyal River contributes only for a few percent to the water in the Ovejas River. However, these effects help understand what could happen to the flow rate of the Ovejas River if similar changes would occur in all tributary rivers at the same time.

The Spatial Water Budget Model (SWBM) has been developed for analyzing temporal and spatial changes in the overall water balance and in stream water availability at a watershed scale. Chapter 2 and 3 explained part of the model. These two chapters focused on the simulation of the potential supply of water in streams over space and time, and the effects of land use changes on the hydrological response of the watershed. Chapter 4 explains how water use and the operation of dams are simulated by SWBM. Domestic, industrial and agricultural water use in the administrative Cabuyal region in 1994-1997 were quantified and simulated. The impact of three hypothetical dams in the Cabuyal River was analyzed too.

## Materials and Methods

### Overview of Simulation Study

#### Simulating water use

Two different types of analyses were carried out with SWBM. The first analysis involved the classification of water availability in the Cabuyal River according to a classification defined by local planning agencies. They expressed water availability as *very low, low, medium* and *high,* based on the per-hectare river flow rate (Table 4-1, 1$^{st}$ and 2$^{nd}$ column). I multiplied these rates with the area of the Cabuyal River watershed (3,246 ha) to determine the corresponding threshold flow rate for the Cabuyal River (Table 4-1, 3$^{rd}$ column). Next, water use in the administrative Cabuyal region during the years 1994 through 1997 was quantified and simulated. Two specific simulation outputs were analyzed: (1) the reduction in flow rate of the Cabuyal River after water use and (2) the percentage of available water that was extracted every day. This simulation did not include dams because there were no dams in the watershed during the 1990s.

#### Simulating dams

The second analysis involved simulating three hypothetical dams in the Cabuyal River to illustrate their impact and potential benefits for regulating river flow rates. Two objectives were considered for modeling the operation of dams. First, the river flow rate (after water extraction) had to be sustained at 34,560 $m^3d^{-1}$ (400 L/s) during the dry season.

Secondly, high flow rates on rainy days in the wet season had to be reduced to 129,600 $m^3d^{-1}$ (1,500 L/s). These simulations were carried out for the same period, 1994-1997. Simulation results were used to calculate the minimum required storage capacities of the dams needed to meet the minimum required flow rate and the maximum allowed flow rate.

Table 4-1. Classification of water availability as used by local planning agencies, and corresponding flow rates of the Cabuyal River. These flow rates were determined by multiplying the corresponding per-hectare flow rate with the area of the watershed, 3246 ha.

| Water availability | --------- Flow Rate --------- | | Typical Water Use |
|---|---|---|---|
| | Per hectare (L/s/ha) | Cabuyal River (L/s) | |
| Very low | < 0.10 | < 325 | Domestic use (people, animals) and irrigation of a 10m x 10m plot per farm. Subsistence level. |
| Low | 0.10 – 0.25 | 325 – 813 | Domestic use (people and animals) and irrigation of 0.5 ha land per farm. Self-sufficiency level |
| Medium | 0.25 – 0.40 | 813 – 1300 | Higher domestic use. Irrigation of 0.8 ha land per farm. Medium level of productivity. |
| High | > 0.40 | > 1300 | Abundant domestic use. Irrigation of the whole farm. Maximum level of productivity. |

Source: J. Rubiano (1999, personal communication).

<u>Watershed Simulation Model</u>

The Spatial Water Budget Model (SWBM) is a continuous simulation, distributed parameter, watershed scale model that simulates water supply and demand over space and time on a daily basis using GIS data structures. The model was designed for analyzing temporal and spatial variation in the overall water balance, stream water flow rates and water availability on a daily basis at a watershed scale. The five major processes that are simulated by SWBM are: (a) land unit water balance, (b) water flow to streams, (c) stream water flow balance, (d) water storage in dams, and (e) water extraction from dams and streams for domestic, agricultural and industrial uses. The model does not simulate storm peak flow, sediment loading, soil erosion or vegetation growth/yield. It can best be applied to hillside watersheds of at least a few hundred hectares but not more than approximately 50,000 ha in size. SWBM has been written in Avenue (ESRI, 1996a) and runs under ArcView GIS v3.1 with the Spatial Analyst (v1.1) and Dialog Designer (v1.0) extensions on Windows and Unix based systems. A detailed description of the land unit water balance and water flow to streams was given in Chapter 3. The description of the model in this chapter focuses on the representation of dams, simulation of water storage in dams, water use from dams and water use from streams. These processes are related to the stream water flow balance.

Stream water flow balance

In a raster GIS, a stream is represented by a series of connected grid cells, each of which receives an accumulated flow beyond some threshold. Figure 4-1 shows components of the water balance for a stream cell. A stream network consists of one or more stream branches. Water in a stream is assumed to flow sufficiently fast so that water inputted into the stream at any point in the watershed will reach the watershed outlet within a day, unless it is (temporarily) stored in a dam or used. This is a reasonable assumption for small watersheds in hillside regions. It has the advantage that the stream water balance for the entire watershed can be calculated using total daily flow volumes for all stream cells.

If a stream is considered as a series of *N* connected grid cells, with grid cell *N* being the watershed outlet (the lowest point in the watershed), then the daily water volume that flows from stream cell *x* to the adjacent downstream cell *x+1* (with $0 < x < N$) is:

$$V_{x,x+1} = V_{x-1,x} + V_{RO,\, x} + V_{LF,\, x} - V_{USE,\, x} - \Delta ST_x, \tag{4-1}$$

where $V_{x-1,x}$ is the flow rate from the neighboring upstream stream cell *x*-1 to stream cell *x*; $V_{RO,\, x}$ and $V_{LF,\, x}$ are the accumulated rates of, respectively, surface runoff and lateral flow into stream cell *x* from adjacent land units; $V_{USE,x}$ is the daily rate of water use from stream cell *x* and $\Delta ST_x$ is the change in volume of water stored in stream cell *x* if that stream cell contains a dam. Notice that $V_{0,1}$ is always zero (beginning point of a stream) and $V_{N,N+1}$ is the amount of water that flows out of the watershed. The unit of all terms in Eq. 4-1 is $m^3d^{-1}$.

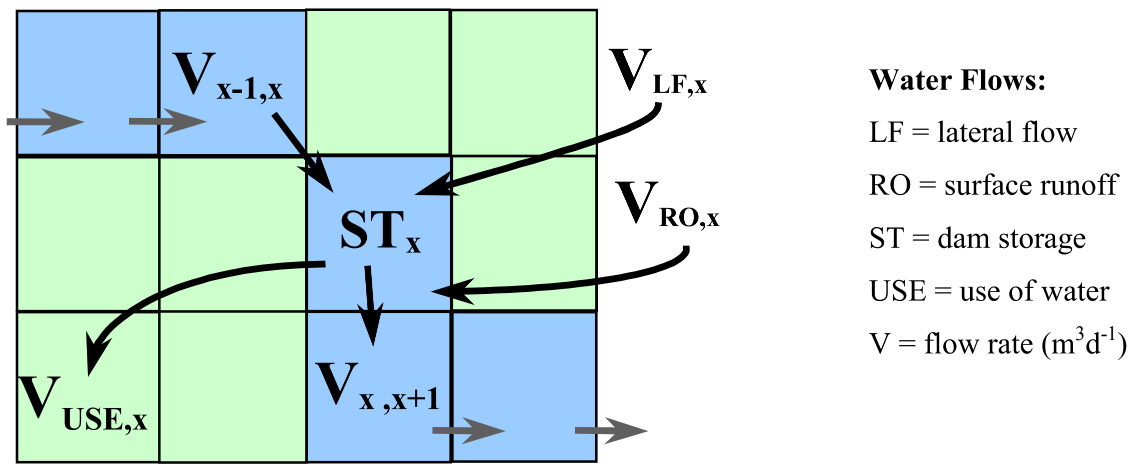


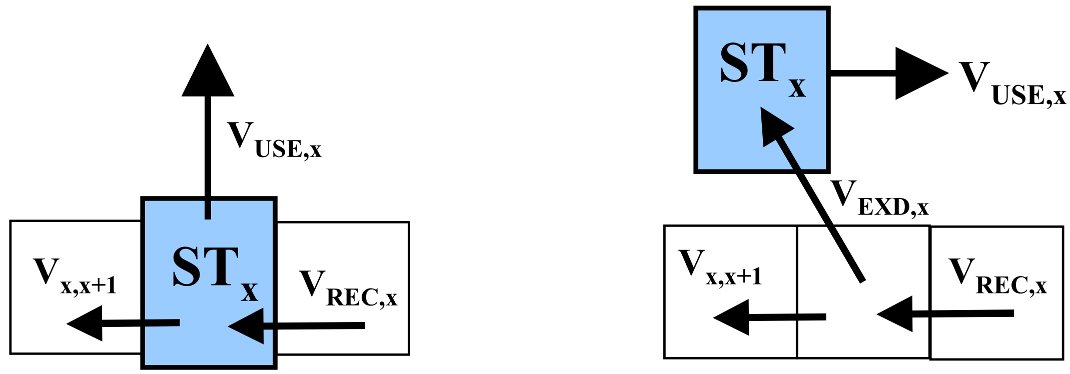

Figure 4-1. Representation of a stream in a raster GIS and components of the stream water balance. The stream cells are blue colored and the land units are green colored.

Representation of dams

Dams may be used for various purposes. First, large amounts of water can be stored in a dam for domestic, industrial or agricultural water use. Small dams can be used to temporarily raise the water level in the river to allow refilling small ponds or water channels by gravity. Water pumps may be used to bring water to external water tanks that provide water storage close to a field or house. This technique is applied by some farmers in the watershed who do not own pumps to extract water from the river for irrigation (de Fraiture et al., 1997). Secondly, a dam can store surplus water during wet periods and return it to the river during dry periods. This is a way to sustain minimum flow rate all year, which may be important to avoid very low downstream water availability and to adequately dilute any contamination. Thirdly, a dam can function as an interruption of the stream flow to reduce storm peak flows, which may help avoid flooding of riverbanks and damage to physical construction in streams after strong rainfall events. A fourth use of dams is hydropower generation. A combination of these uses is possible too.

Any stream cell *x* may be the location of a dam with a specific amount of water in storage, $ST_x$. Each dam is identified by a coordinate pair *(x,y)*, which is determined from a map on the screen. Stream cells *x* that are not dams are assumed to have a zero storage capacity. Two different types of dams can be simulated in SWBM. The first type is a dam constructed in the river (Fig. 4-2A). Typically, the storage area of the dam is a basin located adjacent to the river. Water can be extracted directly from the dam to meet domestic, industrial and agricultural water demands. This dam can also be used to control river flow rates. The second dam type is a large basin external to the river and connected to it via pumps and pipes (Figure 4-2B). Water use is taken from the reservoir, not from the stream cell directly. Water can flow only from the river to the reservoir, not in opposite direction. Stream cell *x* itself cannot store any water. Consequently, this dam cannot be used to control river flow rates. The physical dimensions of a dam required to realize a certain storage capacity and the construction and daily operation of dams are engineering aspects that are assumed technically feasible but are not taken into account by SWBM.

Several model parameters must be specified to characterize the size and operation of dams that are built in the stream. Only a subset of these parameters applies to dams that are external reservoirs. Parameter values may vary on a daily basis and must therefore be specified for every day Julian *d*. Alternatively, a parameter value may also be specified as a constant value over some period $d_1..d_2$ (as long as the entire year), in which case the model assigns the same value to the all days within that period. All parameters are entered through menus via SWBM's GIS user-interface and are stored in dBase files.




(A) $\frac{\Delta ST}{\Delta t} = V_{REC,x} - V_{x,x+1} - V_{USE,x}$

(B) $\frac{\Delta ST}{\Delta t} = V_{EXD,x} - V_{OUT,x}$

Figure 4-2. Two possible ways to simulate dams in SWBM. a) Dams are built in the stream. b) Dams are built as external reservoirs connect to the stream.

Storage capacity ($ST_{MX,x}$, $m^3$). This is the maximum amount of water that can be held in the dam, including any water tanks, small ponds and artificial lakes that may be connected to the dam. The storage capacity is a physical property that is constant over time.

Water intake settings. There are no water intake settings for a dam that is built in the river because such dam blocks the entire stream. The rate of water flow into the dam is equal to the total receiving flow $V_{REC,x}$. For an external dam (Fig. 4-2B), the gross rate of water flow into the dam, $V_{EXD,x}$ ($m^3d^{-1}$), is calculated from a maximum specified value $V_{EXDMX,x}$, the present storage in the dam and water extraction. It cannot exceed total receiving flow in the river, $V_{REC,x}$. If the dam is full, i.e. $ST_x = ST_{MX,x}$, all receiving water will overflow.

Water release settings. This only applies to a dam built in the river. The rate of water release from a dam may be specified as a fixed rate, $V_{OUT,x,d}$ ($m^3d^{-1}$). Alternatively, a fraction $FR_{ST,x,d} = ST_{x,d}/ST_{MX,x}$ (between 0 and 1) may be specified. The model will then automatically calculated the appropriate rate of water release such that storage in the dam is kept at the desired level. This allows keeping storage in the dam at near equilibrium. The dam is kept empty with a $FR_{ST,x,d}$ value of 0, whereas the dam is kept at storage capacity with a $FR_{ST,x,d}$ value of 1. Daily water release can never exceed the available amount of water in the dam.

Minimum required flow ($V_{MIN,x}$, $m^3d^{-1}$). This is an optional setting, which applies only to a dam that is built in the river. If specified, the rate of water release from the dam may be increased as needed to meet the minimum downstream flow requirement. It may be impossible to meet a minimum flow requirement if the dam is empty. Typically, a minimum required flow is combined with a high value for $FR_{ST,x,d}$ (near or equal to 1). Storage in the dam is then kept high to provide sufficient additional water when river flow rates are low.

Maximum allowed flow ($V_{MAX,x}$, $m^3d^{-1}$). This is an optional setting for a dam that is built in the river. If specified, the rate of water release may be decreased as needed to meet the maximum allowed downstream flow requirement. It may be impossible to meet a maximum allowed flow if the dam is full (no remaining buffer capacity). Typically, a maximum allowed flow is combined with a low value of $FR_{ST,x,d}$ (near or equal to 0). Storage in the dam is then kept low to provide sufficient buffer capacity.

A minimum required flow and a maximum allowed flow may apply simultaneously. The former must always be smaller than the latter. In this case it is important that the value of $FR_{ST,x,d}$ is chosen around 0.5, so that the dam can adequately function in either direction.

Simulating water use and dam operation

Water may be extracted from any stream cell or dam *x* at any Julian day *d* for domestic use ($V_{DOM,x,d,}$, $m^3d^{-1}$), industrial use ($V_{IND,x,d}$, $m^3d^{-1}$) and agricultural uses ($V_{AGR,x,d}$, $m^3d^{-1}$). Typically, water is extracted only from a limited number of specific locations. Examples of such locations are places where water is diverted into a drinking water system, where farmers place pumps or refill small ponds for irrigation purposes, near cassava and sugarcane processing industries, and at dams. Each stream cell *x* where water is extracted is identified by a coordinate pair *(x,y).* These locations are georeferenced and selected from a map on the screen. Water use may vary from day to day. The three water use rates must therefore be specific for each Julian day *d* and for each location *x*. Alternatively, each rate can also be specified as a constant value over some period $d_1..d_2$, in which case the model will automatically assign the same rate to all days within that period. Water use rates do not have to be specified if they are zero. All water use data are entered through menus of SWBM's ArcView GIS user-interface and are stored in dBase files.

Water use from stream cells and water storage in dams are simulated on a daily basis. This is done for the stream cells in downstream direction, i.e. starting with the stream cell at the highest elevation and ending with the most downstream stream cell. Changes in river flow rates are then properly accumulated through the stream network towards the outlet.

Case 1. Water use from a stream cell without dam. On any day *d,* the rate of receiving water in stream cell *x*, $V_{REC,x}$ ($m^3d^{-1}$), is the sum of all incoming water flows (Fig. 4-1):

$$V_{REC,x,d} = V_{x-1,x,d} + V_{RO,x,d} + V_{LF,x,d}. \tag{4-2}$$

The total rate of water use from stream cell *x* on day *d*, $V_{USE,x,d}$ ($m^3d^{-1}$), is the sum of the domestic, industrial and agricultural uses (not all terms need to be defined):

$$V_{USE,x,d} = V_{DOM,x,d} + V_{IND,x,d} + V_{AGR,x,d}. \tag{4-3}$$

The amount of water used cannot exceed the amount of water in the river. The rate of stream flow from stream cell *x* to *x*+1, $V_{x,x+1,d}$ ($m^3d^{-1}$), is calculated as:

$$V_{x,x+1,d} = V_{REC,x,d} - V_{USE,x,d} \qquad \text{if } V_{REC,x,d} > V_{USE,x,d} \text{ and} \tag{4-4}$$

$$V_{x,x+1,d} = 0 \qquad \text{if } V_{REC,x,d} \leq V_{USE,x,d}.$$

If the supply of water is insufficient to meet the water demand, i.e., $V_{REC,x,d} < V_{USE,x,d}$, highest priority is given to meeting domestic water demand, then industrial water demand and lastly agricultural water demand. This reflects the actual preferences of stakeholders and water allocation practices in the Cabuyal River watershed (de Fraiture et al., 1997).

Case 2. Water use from a dam that is external to stream. Equations 4-2 and 4-3 apply in this case too. On any day *d*, the rate of water flow into the dam, $V_{EXD,x,d}$ ($m^3d^{-1}$), is calculated as the rate needed to completely fill the dam after water extraction takes place, but not exceeding the rate of receiving water in stream cell *x* ($V_{REC,x,d}$) or the specified maximum rate ($V_{EXDMX,x,d}$):

$$V_{EXD,x,d} = Min\ \{ST_{MX,x} - ST_{x,d-1} - V_{USE,d},\ V_{EXDMX,x,d},\ V_{REC,x,d},\}, \qquad (4\text{-}5)$$

where *Min* indicates that the lowest of the three arguments is taken. The new storage in the dam at the end of the day (after water extraction), $ST_{x,d}$, is then calculated as

$$ST_{x,d} = ST_{x,d-1} + V_{EXD,x,d} - V_{USE,x,d} \qquad \text{if } V_{EXD,x,d} + ST_{x,d-1} > V_{USE,x,d} \text{ and} \qquad (4\text{-}6)$$

$$ST_{x,d} = 0 \qquad \text{if } V_{EXD,x,d} + ST_{x,d-1} \leq V_{USE,x,d}$$

The priorities for water allocation are the same as in Case 1: domestic water demand is met first, then industrial water demand and lastly agricultural water demand. The first argument of the *Min* function in Equation 4-5 allows keeping the dam at storage capacity at the end of the day after water use, providing that the supply of water is sufficient.

The rate of stream flow from stream cell *x* to *x*+1 is calculated as:

$$V_{x,x+1,d} = V_{REC,x,d} - V_{EXD,x,d} \qquad \text{if } V_{REC,x,d} > V_{EXD,x,d} \text{ and} \qquad (4\text{-}7)$$

$$V_{x,x+1,d} = 0 \qquad \text{if } V_{REC,x,d} \leq V_{EXD,x,d}.$$

Case 3. Water use from a dam that is built in stream. This is the most complicated case because various operational settings of the dam must be accounted for in a specific order. First, the total supply rate of water, $V_{TOT,x,d}$ ($m^3d^{-1}$) is calculated as the receiving water in stream cell *x* plus yesterday's storage in the dam:

$$V_{TOT,x,d} = V_{x-1,x,d} + V_{RO,\,x,d} + V_{LF,\,x,d} + ST_{x,d-1}. \tag{4-8}$$

$V_{TOT,x,d}$ is potentially extractable. If all of it would be used on a single day, there would not be any water left in neither the stream nor the dam. The remaining water after water extraction, $V_{REM,x,d}$ ($m^3d^{-1}$ ), is calculated as:

$$V_{REM,x,d} = V_{TOT,x,d} - V_{USE,x,d} \qquad \text{if } V_{TOT,x,d} > V_{USE,x,d} \text{ and} \tag{4-9}$$

$$V_{REM,x,d} = 0 \qquad \text{if } V_{TOT,x,d} \leq V_{USE,x,d}.$$

If water release out of the dam was specified by a value $FR_{ST,x,d}$ rather than a fixed rate $V_{OUT,x,d}$, a preliminary value of the latter ($m^3d^{-1}$) is the calculated as:

$$V_{OUT,x,d} = V_{REMx,d} \cdot FR_{ST,x,d}. \tag{4-10}$$

Initially, the actual rate of water flow out of the dam ($V_{x,x+1,d}$) is set to $V_{OUT,x,d}$. It may be necessary to correct for any minimum required and maximum allowed flow rate that have been specified, or if the remaining amount of water $V_{REMx,d}$ is not enough. This accounting is carried out by first calculating the new storage in the dam, and only then the actual rate of water flow out of the dam. Four different situations are considered, which differ in the way the new storage in the dam is calculated.

Case 3a. If neither a minimum required flow nor a maximum allowed flow have been specified, the new storage in the dam, $ST_{x,d}$, is computed as:

$$ST_{x,d} = Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{OUT,x,d}\},\tag{4-11}$$

and the rate of stream flow from stream cell *x* to *x*+1, $V_{x,x+1}$ ($m^3d^{-1}$), is calculated as:

$$V_{x,x+1,d} = V_{REM,x,d} - ST_{x,d}.\tag{4-12}$$

Case 3b. If only a minimum flow requirement has been specified (i.e., $V_{MIN,x,d} > 0$) but no maximum allowed flow, then the new storage in the dam, $ST_{x,d}$, is given by:

$$\begin{aligned}
ST_{x,d} &= Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{OUT,x,d}\} && \text{if } V_{MIN,x,d} \le V_{OUT,x,d} && \text{(4-13)}\\
ST_{x,d} &= Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{MIN,x,d}\} && \text{if } V_{OUT,x,d} < V_{MIN,x,d} < V_{REM,x,d}\\
ST_{x,d} &= 0 && \text{if } V_{MIN,x,d} \ge V_{REM,x,d}.
\end{aligned}$$

Use of the *Min* function ensures that the maximum storage capacity storage ($ST_{MX,x}$) is never exceeded. The rate of water flow out of the dam ($V_{x,x+1}$) is calculated with Equation 4-12. This flow rate may be below the minimum required flow rate if the dam was empty.

Case 3c. If only a maximum allowed flow has been specified (i.e., $V_{MAX,x,d} > 0$) but no minimum required flow, the new storage in the dam, $ST_{x,d}$, is computed as:

$$\begin{aligned}
ST_{x,d} &= Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{OUT,x,d}\} && \text{if } V_{OUT,x,d} \le V_{MAX,x,d} \text{ and} && \text{(4-14)}\\
ST_{x,d} &= Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{MAX,x,d}\} && \text{if } V_{OUT,x,d} > V_{MAX,x,d}.
\end{aligned}$$

The rate of water flow out of the dam ($V_{x,x+1}$) is again calculated with Equation 4-12. This flow rate may be above the maximum allowed flow rate if the dam was full.

Case 3d. If a both a minimum required flow and a maximum allowed flow have been specified (i.e., $0 < V_{MIN,x,d} < V_{MAX,x,d}$), then the new storage in the dam is given by:

$$ST_{x,d} = Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{MIN,x,d}\} \qquad \text{if } V_{OUT,x,d} \le V_{MIN,x,d} \qquad (4\text{-}15)$$

$$ST_{x,d} = Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{OUT,x,d}\} \qquad \text{if } V_{MIN,x,d} < V_{OUT,x,d} < V_{MAX,x,d}$$

$$ST_{x,d} = Min\ \{ST_{MX,x}, V_{REM,x,d} - V_{MAX,x,d}\} \qquad \text{if } V_{OUT,x,d} \ge V_{MAX,x,d}.$$

The rate of water flow out of the dam ($V_{x,x+1}$) is again calculated with Equation 4-12.

## Quantification of Water Use in the Mid 1990s

### Domestic water use

CIAT carried out a census in the administrative Cabuyal region in 1995. A total of 910 families with 5,357 people were living in 22 communities in the region at that time (Table 4-2). Per capita domestic water use in a rural area like the Cabuyal region was estimated at 0.120 $m^3d^{-1}$ (Ramirez, 1992), resulting in a total domestic water use of 643 $m^3d^{-1}$ (7.4 L/s) in the administrative Cabuyal region. This rate is assumed constant all year.

About 15% of the inhabitants in the administrative Cabuyal region obtained drinking water from wells or directly from streams, whereas the remaining 85% had access to a drinking water system (Table 4-2), locally known as *acueducto* (de Fraiture et al., 1997). A drinking water system is a network of small pipes in the watershed. Part of the stream water in the upper part of the watershed is diverted into these pipes, from where it flows (by gravity) to the houses. There were a total of 9 drinking water systems, with a combined supply capacity of 2,591 $m^3d^{-1}$ (30.0 L/s) (Table 4-3). Three drinking water systems (Laguna-Pescador, El Cidral and Santa Barbara) took water from the Cabuyal River or a tributary at a combined rate of 1,555 $m^3d^{-1}$ (18.0 L/s). The other six systems took water from streams outside the Cabuyal River catchment at a rate of 1,036 $m^3d^{-1}$ (12.0 L/s). These rates are assumed constant all year, unless the river flow rate is less.

Table 4-2. Total area, population size, population density and access to drinking water for the 22 communities of the 7,526 ha administrative Cabuyal region, Colombia.

| Community | -------- Area ------- | | ---- Population ---- | | Drinking water system [1] | | |
|---|---|---|---|---|---|---|---|
| | ha | frac[2] | # | $km^{-2}$ | Inside | Outside | None |
| Buena Vista | 899 | 0.50 | 210 | 23 | 0 | 201 | 9 |
| Cabuyal | 552 | 0.26 | 248 | 45 | 0 | 248 | 0 |
| Crucero | 122 | 0.46 | 258 | 212 | 236 | 0 | 22 |
| El Caimito | 694 | 0.00 | 186 | 27 | 120 | 0 | 66 |
| El Cidral | 348 | 1.00 | 351 | 101 | 351 | 0 | 0 |
| El Oriente | 477 | 0.81 | 48 | 10 | 0 | 32 | 16 |
| El Porvenir | 214 | 0.24 | 223 | 59 | 223 | 0 | 0 |
| El Rosario | 380 | 0.00 | 400 | 187 | 0 | 305 | 95 |
| El Socorro | 496 | 0.49 | 369 | 74 | 369 | 0 | 0 |
| La Campina | 230 | 0.44 | 174 | 76 | 163 | 0 | 11 |
| La Esperanza | 244 | 0.21 | 158 | 65 | 0 | 124 | 34 |
| La Isla | 221 | 0.37 | 104 | 47 | 0 | 104 | 0 |
| La Laguna | 396 | 0.31 | 412 | 104 | 288 | 0 | 124 |
| La Llanada | 237 | 1.00 | 186 | 79 | 62 | 0 | 124 |
| La Primavera | 157 | 0.00 | 92 | 59 | 0 | 92 | 0 |
| Los Quingos | 301 | 0.37 | 435 | 144 | 335 | 0 | 100 |
| Palermo | 333 | 0.53 | 191 | 57 | 58 | 0 | 133 |
| Panamericana | 252 | 0.41 | 199 | 79 | 0 | 195 | 4 |
| Pescador | 115 | 0.00 | 225 | 196 | 225 | 0 | 0 |
| Potrerillo | 240 | 1.00 | 268 | 112 | 230 | 0 | 38 |
| Santa Barbara | 340 | 0.56 | 325 | 96 | 81 | 221 | 23 |
| Ventanas | 276 | 0.40 | 295 | 107 | 0 | 295 | 0 |
| TOTAL | 7526 | 0.43 | 5357 | 71 | 2741 | 1817 | 799 |

Source: De Fraiture et al. (1997), based on a survey that CIAT carried out in 1994.

[1] "Inside" and "outside" refer to a drinking water system that draws water from, respectively, inside and outside the Cabuyal River catchment; "None" means no access to any drinking water system.

[2] Fraction of a community that falls within the catchment of the Cabuyal River.

Table 4-3. Drinking water systems in the administrative Cabuyal region[1]. The water sources of the systems indicated with a star (*) are located within the Cabuyal River watershed.

| | Name [2] | Beneficiaries # | Water source | Supply ($m^3d^{-1}$) |
|---|---|---|---|---|
| 1 | Laguna–Pescador* | 2,309 | Cabuyal River | 1,296 |
| 2 | Carrizales | 748 | Carrizal River | 432 |
| 3 | St. Barbara-Ventanas | 516 | Guaycoche River | 173 |
| 4 | El Cidral* | 351 | Quebrada La Colorada | 173 |
| 5 | El Rosario | 305 | unknown | 173 |
| 6 | El Oriente | 32 | unknown | 86 |
| 7 | La Esperanza | 124 | unknown | 86 |
| 8 | Primavera | 92 | unknown | 86 |
| 9 | St. Barbara* | 81 | Quebrada La Colorada | 86 |
| | TOTAL | 4,558 | | 2,591 |

[1] Source: de Fraiture et al. (1997), based on data from the early 1990s.
[2] Many names of drinking water systems coincide with community names.

Figure 4-3 shows the water intake of the largest drinking water system, Laguna-Pescador. This location (W 76.511º and N 2.732º) is in the top of the watershed, just down-stream from the point where the Cabuyal River emerges from springs. The flow rate of the river is very low at this point. The picture was taken on 24 June 1998, at the start of the dry season. The construction of the drinking water system is simple. Part of the stream water flows through a metal filter that keeps leaves and twigs out of the drinking water. Water then flows into the small basin with a volume of approximately 1 $m^3$, from where it flows further in a pipe (not visible in Figure 4-3) that has a diameter of about 15cm, towards the houses. Drinking water is not chemically treated.

Figure 4-3. Starting point of the largest drinking water system (Laguna-Pescador). Part of the stream water flows through the metal filter into the small concrete basin. From there it flows into a pipe (not visible) and farther toward the houses.

Figure 4-4 shows the geographical extent of the 22 communities in the administrative Cabuyal region and Figure 4-5 shows the location of all 910 houses and the roads. Some 70% of the houses are located within 150m of a road. Table 4-2 gives the area and population of each community and indicates how the inhabitants obtained drinking water in each community. Access to drinking water system was spatially variable. For example, the community of La Llanada is located entirely within the catchment of the river but only 62 out of 182 inhabitants had access to a drinking water system. On the other hand, the communities of El Caimito, Pescador and El Rosario fall entirely outside the actual catchment area, nevertheless all families living here were connected to a drinking water system. In total, 51% of all inhabitants have access to drinking water system that draws water from within the Cabuyal River catchment, 34% get piped drinking water from outside the catchment, and 15% of the inhabitants are not connected to any drinking water system. They obtained drinking water from wells or directly from streams.

Simulation of domestic water use by SWBM required the specification of the net daily rate of domestic water use from the Cabuyal River. This rate was 1,555 $m^3d^{-1}$ (18 L/s), the supply by the Laguna-Pescador, El Cidral and Santa Barbara systems. It was assumed constant during the years 1994-1997. The locations of water extraction are given in Figure 4-7A. The corresponding water extraction rates are those in Table 4-2. This selection of the rate of 1,555 $m^3d^{-1}$ may seem confusing. On one hand, the combined rate of water supply by all drinking water systems is higher (2,591 vs. 1,555 $m^3d^{-1}$). However, water extraction from streams outside the Cabuyal River catchment must not be accounted for. On the other hand, the estimated rate of actual domestic water use is lower (643 vs. 1,555 $m^3d^{-1}$). Any unused drinking water was assumed to leave the drinking water systems in the lowest lying community of El Socorro, which is beyond the end point of the Cabuyal River and outside the catchment of the river. Surplus water was not returned to the river and was, therefore, considered used within the watershed.

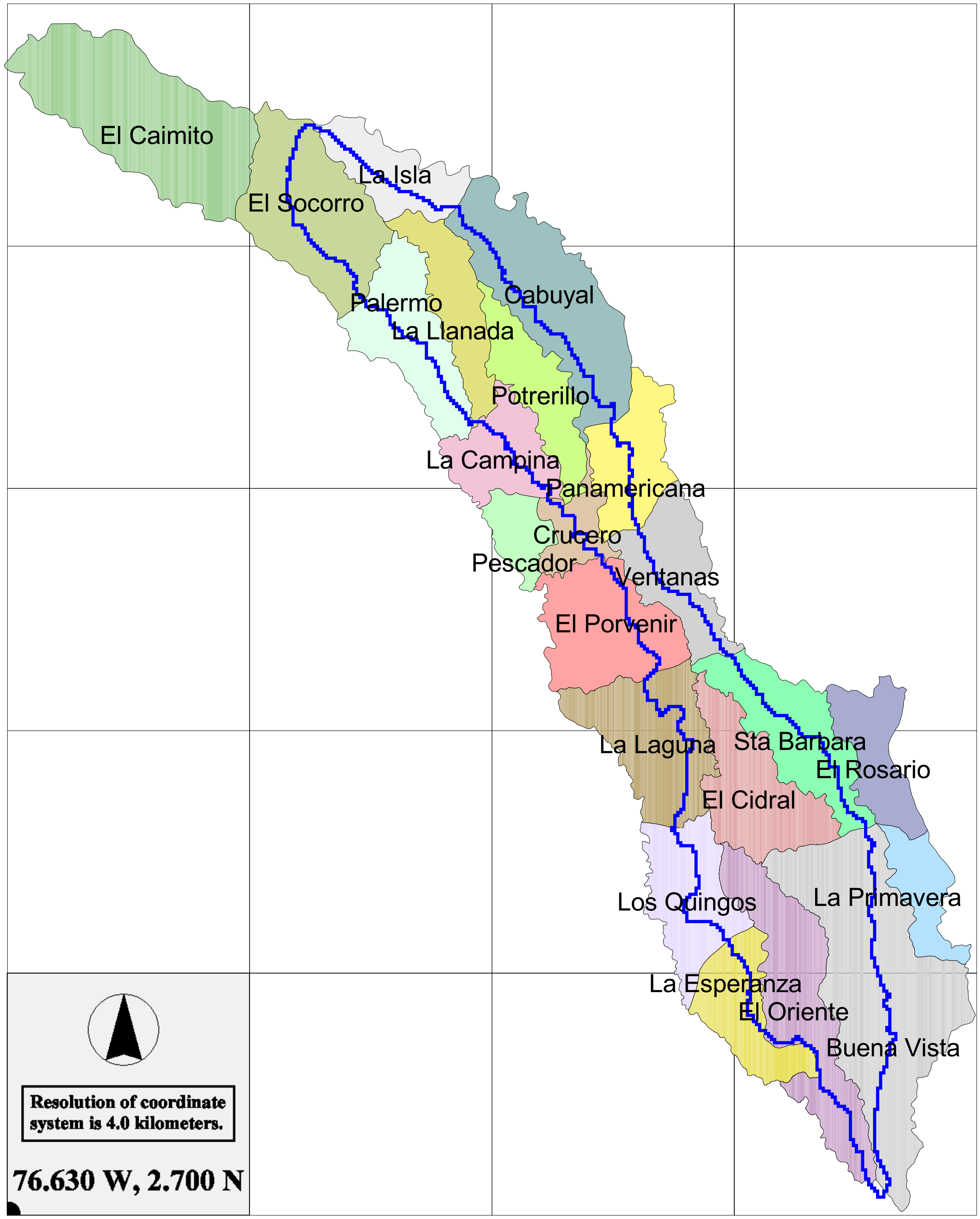



Figure 4-4. Geographical location of the 22 communities of the administrative Cabuyal region. The total area of the administrative watershed is 7,526 ha. The thicker blue line indicates the boundary of the 3,246 ha Cabuyal River watershed.

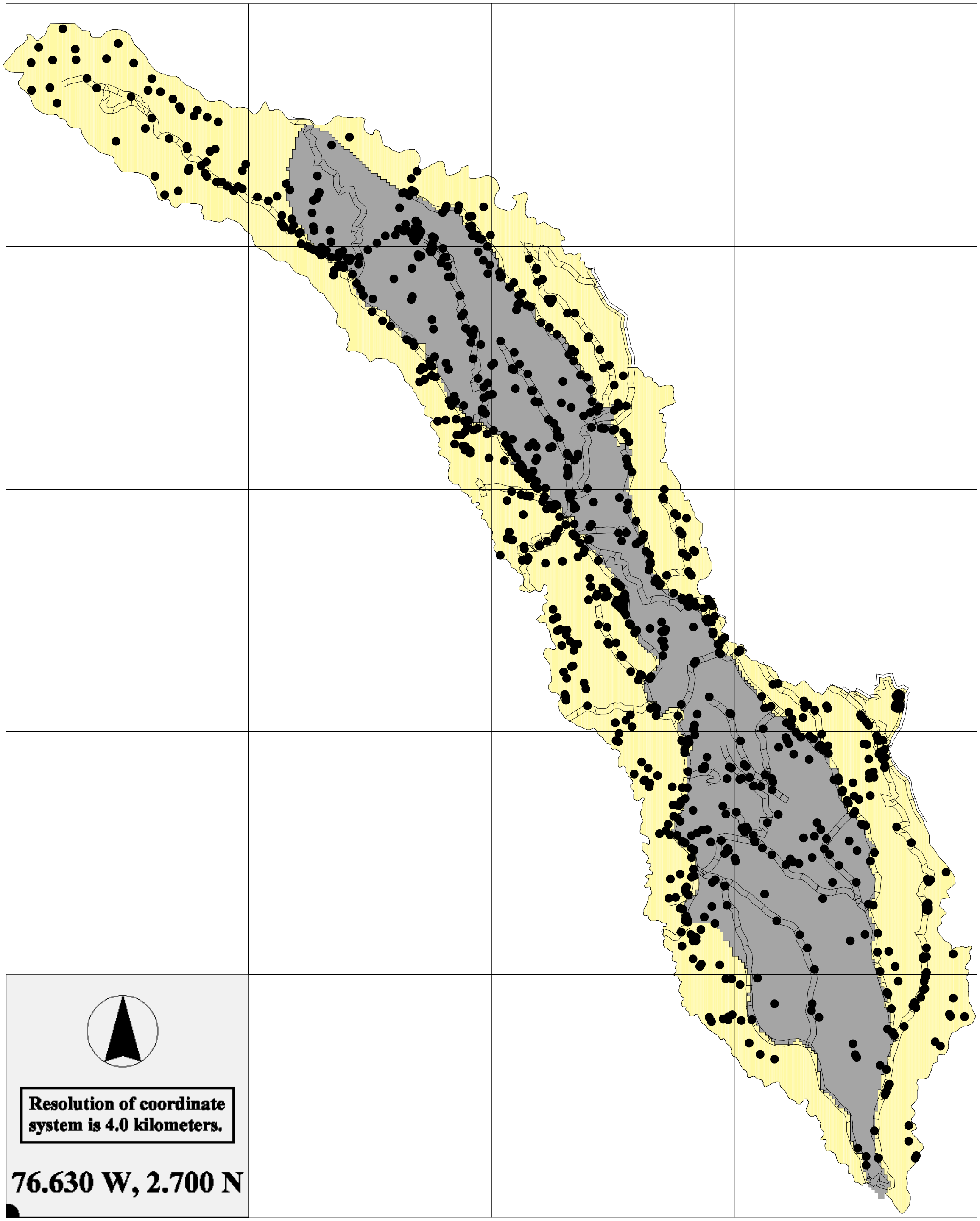



Figure 4-5. Location of roads (double lines) and 910 houses (dots) within the administrative Cabuyal region. The darker colored area is the Cabuyal River watershed. About 56% of the houses are located within the catchment. About 70% of the houses are within 150 m of a road, 15% are between 150 and 300m, and 15% are at a distance greater than 300m.

Industrial water use

Relatively little industrial activity took place in the administrative Cabuyal region. All industries involved farm-based processing of agricultural products. They include 2 sugarcane processing plants, 2 milk and cheese processing plants, 17 farms that process a total of 5900 chickens (de Fraiture et al., 1997), 3 major cassava processing plants and a dozen small farms that process cassava (E.B. Knapp, 1999, personal communication).

The three cassava processing plants are the largest industrial water consumers. River water is extracted from the river to wash and process cassava roots. In 1995, a total of 940 tons of starch was produced (E.B. Knapp, 1999, personal communication). The three major plants accounted for nearly 50% of this production. The rule of thumb is that 5 tons of cassava root and 30 $m^3$ water is needed to produce 1 ton of starch. Cassava industries generally operate all year around. The average rate of water use by the cassava industries is then 78 $m^3d^{-1}$ (0.9 L/s). This water was taken in equal rates from three different locations from the river (where the three largest cassava processing plants are located, Figure 4-7A). All other industries used an estimated 12 $m^3d^{-1}$ (0.14 L/s), which was taken from the drinking water system (de Fraiture et al., 1997).

Industrial water use is very low compared to domestic and agricultural water use, as shown in Figure 4-6. It is also low in absolute terms because less than 0.5% of the river flow in the dry season and less than 0.1% in the wet season is used by industries. However, there is concern about the potential impact of industries on water quality (CIAT, 1993; de Fraiture et al., 1997). Part of the processing water is discharged back into the river. High concentrations of starch and plant residue may pollute the stream and increase biological oxygen demand. This may cause a health treat to the population and threaten in situ use of the river for fishery activities (de Fraiture et al., 1997). The newwest cassava plant has a 3-way filtering system to reduce water contamination (J. Rubiano, 1999, personal communication).

Irrigation water demand

Irrigation is mostly applied to tomatoes, although it is used at a smaller scale for beans, peas, onion, papaya, potato and blackberries (de Fraiture et al., 1997). Irrigated tomatoes are appealing because they can be sold on the market (Ostertag, 1996) and because cropping schemes that include tomato increases long-term farm sustainability (Hansen et al., 1997). Tomatoes are typically grown from April through September because this period fits well within the crop rotation (Hansen, 1996) and the risk for crop losses due to pests and diseases is smallest in the drier months. Farmers would not grow tomatoes during the dry season if they cannot irrigate them because the risk for crop losses due to drought would be unacceptably large (de Fraiture et al., 1997). A farm-level survey showed that farmers obtain irrigation water from streams and from the drinking water system (Table 4-4).

Local farmers do not measure and have little idea about the amount of irrigation water they use (de Fraiture et al., 1997). I used the CROPGRO v3.5 (98.0) crop growth model to estimate irrigation water requirements for field-grown tomato. CROPGRO is part of the Decision Support System for Agrotechnology Transfer (DSSAT) v3.5 (Hoogenboom et al., 1994) and has been adapted to simulate field-grown tomato (Scholberg et al., 1996).

Table 4-4. Irrigated area and irrigation method in the administrative Cabuyal region in 1995.

| Irrigation method and water source | # farmers | Irrigated area (ha) |
|---|---|---|
| Drinking water system | 280 | 84 |
| Stream water, motor pumps | 33 | 15 |
| Stream water, by gravity | 7 | 1 |

Source: de Fraiture et al. (1997).

Two different types of simulations were carried out, with different planting dates and weather data. Genetic coefficients for the tomato variety *Sunny Semi-Determinate* were used, which were included with the DSSAT software. Soil parameters were based on soil analysis on the Jose Domingo farm (Hansen, 1996). An amount of 75 kg N $ha^{-1}$ was applied at the day of transplanting and at 35 days after transplanting. This is the typical fertilizer application schedule of at the Jose Domingo farm (Hansen and Jones, 1996). A 1-month fallow period was simulated prior to transplanting so that soil water could reach a level that was typical for that time of the year. The soil water content was assumed at 50% plant available water at the start of the fallow period. Irrigation was applied at a rate of 8 mm per application whenever the soil water content in the top 30 cm reached 40% plant available water. An irrigation efficiency of 0.75 was assumed.

<u>Simulation of 1994-1997 with actual weather data</u>. Four years (1994-1997) of weather data measured at the Domingo farm were used. Hansen et al. (1997) reported an earliest tomato transplanting date of March 21 for the Jose Domingo farm. Two different planting dates were simulated. Planting on April 1 was simulated as it corresponds close to the reported earliest planting date. Planting on May 1 was also simulated. The dry months of June-September then fall completely within the growing season--particularly the vegetative and reproductive stages. Table 4-5 gives the simulated monthly irrigation water requirements for planting on May 1. As expected, irrigation water requirements in every month were slightly lower for planting on April 1 (not shown). Irrigation water demand was highest in August 1997, on average 5.2 mm $d^{-1}$. Irrigation was never needed in May.

Based on the data in Table 4-5, total irrigation water use ($m^3d^{-1}$) was calculated if 100 ha were irrigated from June through September (Table 4-6 and Figure 4-6). Irrigation was applied to 100 randomly selected land units (each 1 ha) classified as *Cropped Land* in Figure

3-7. Irrigation water use was assumed constant on all days within the same month, based on the assumptions that (1) farmers would not irrigate all at the same time and (2), on rainy days, water would still be extracted to refill irrigation ponds and water tanks rather than immediately application. Notice that an amount of 1000 $m^3d^{-1}$ is needed to irrigation 100 ha at a rate of 1 mm $d^{-1}$. No irrigation was applied from October through May.

Irrigation water was taken from streams in equal amounts at 25 locations throughout the watershed; 12 locations were in the Cabuyal River (the main stream) and 13 locations were in smaller tributary streams (Figure 4-7). These locations were chosen to simulate a fairly evenly distributed irrigation water use throughout the watershed. The actual locations where farmers extracted water from streams in 1994-1997 was unknown. The highest rate of irrigation water use at any of the 25 locations was 200 $m^3d^{-1}$ (2.31 L/s) in August 1997.

Table 4-5. Measured rainfall and simulated duration and monthly irrigation requirements during the growing season for tomato planted on May 1 in the Cabuyal River watershed. An irrigation efficiency of 0.75 was assumed.

| Planting | [---Growing Season ---] | | [------ Irrigation Water Requirements -----] | | | |
|---|---|---|---|---|---|---|
| | Rainfall (mm) | Length (days) | JUN | JUL | AUG | SEP |
| | | | ---------------- (mm $month^{-1}$) ----------------- | | | |
| May 1, 1994 | 393 | 145 | 15 | 60 | 145 | 105 |
| May 1, 1995 | 746 | 143 | 0 | 10 | 0 | 30 |
| May 1, 1996 | 336 | 142 | 10 | 15 | 100 | 40 |
| May 1, 1997 | 371 | 142 | 0 | 65 | 155 | 5 |

Table 4-6. Estimated irrigation water use for 100 ha of field-grown tomato in the Cabuyal River watershed, for 4 planting dates. An irrigation efficiency of 0.75 was assumed.

| Planting | June | July | August | September |
|---|---|---|---|---|
| | ----------------------- Irrigation Water Use ($m^3d^{-1}$) ---------------------- | | | |
| May 1, 1994 | 500 | 1,935 | 4,677 | 3,500 |
| May 1, 1995 | 0 | 323 | 0 | 1,000 |
| May 1, 1996 | 333 | 484 | 3,226 | 1,333 |
| May 1, 1997 | 0 | 2,097 | 5,000 | 161 |

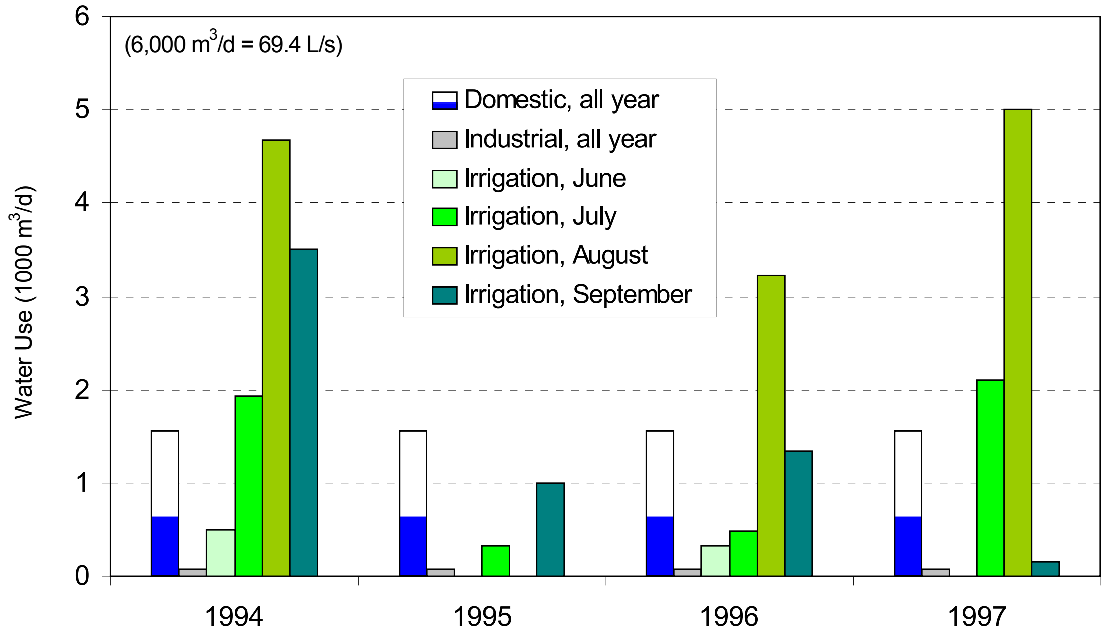



Figure 4-6. Average daily water use from 1994 through 1997 in the 7,250 ha administrative Cabuyal region. Domestic and industrial water use is constant all year. Irrigation was applied only from June through September; it was assumed constant within a month. The white part of the "domestic" bar indicates unused water (surplus intake) of the drinking water systems.

Simulation of 100 years with generated weather data. The data in Table 4-5 did not give a good indication of the typical irrigation water requirements in the Cabuyal River watershed because irrigation water demand varied significantly between the four years caused by large differences in the amount and distribution of precipitation during the growing season (see Table 3-6). In addition, irrigation water requirements for September only applied to part of that month because the growing season ended before the end of the month. Irrigation water requirements in September might have been higher for a tomato crop that was planted later and was growing and/or productive during the entire month of September.

A second simulation was carried out to estimate the long-term average irrigation water requirements in the Cabuyal River watershed. Twelve cropping seasons were analyzed, by transplanting tomato on the first day of each month. The possible effects of pests and diseases on plant growth during the wet months were not accounted for. The WeatherMan software (Pickering et al., 1994) was used to generate 100 years of daily rainfall, minimum and maximum temperature and solar radiation. I used weather generator coefficients that were estimated by Hansen (1996) based on weather data from six weather stations in, or close to, the Cabuyal River watershed. Each cropping season was simulated with the 100 replicates of weather data. Irrigation water requirements were averaged over these years. All other simulation parameters remained the same as in the first simulation.

Simulated long-term average irrigation water demand is given in Table 4-7. Irrigation was not needed from November through May. Tomatoes planted in May had the lowest rainfall during the growing season (840 mm), the largest total irrigation water need (119.5 mm) and a highest water demand of 1.59 mm $d^{-1}$ in August. Total irrigation water demands are also high for tomatoes planted in April (85.1 mm), June (100.2 mm) and July (98.7 mm) with irrigation water demand always greater than 1.25 mm $d^{-1}$ in August. The irrigation requirements in August 1994 and August 1997 were more than 3 times the long-term average water demand in August, and in August 1996 it was more than twice as high. This indicates that the summers of 1994, 1996 and 1997 were much drier than average. The data in Table 4-7 are not used for simulation in this chapter, but they are used to quantify irrigation water use for the scenarios in Chapter 6.

Table 4-7. Measured rainfall, simulated growing season length, and simulated monthly irrigation requirements for field-grown tomato planted at the 1 day of each month, averaged over 100 replicates. Irrigation was never needed from November through May.

| Planting | Growing Season Rainfall (mm) | Length (days) | JUN | JUL | AUG | SEP | OCT | TOTAL |
|---|---|---|---|---|---|---|---|---|
| | | | Irrigation Water Requirements (mm month$^{-1}$) | | | | | |
| 1 JAN | 1231 | 157 | - | - | - | - | - | - |
| 1 FEB | 1110 | 156 | 9.9 | 6.7 | - | - | - | 16.6 |
| 1 MAR | 1012 | 154 | 10.7 | 32.8 | 2.3 | - | - | 45.7 |
| 1 APR | 912 | 152 | 10.1 | 38.7 | 36.3 | - | - | 85.1 |
| 1 MAY | 840 | 155 | 10.8 | 40.1 | 47.7 | 21.9 | - | 119.5 |
| 1 JUN | 906 | 160 | - | 25.1 | 44.8 | 28.0 | 2.4 | 100.2 |
| 1 JUL | 989 | 162 | - | 18.9 | 39.1 | 28.9 | 2.8 | 89.7 |
| 1 AUG | 1085 | 162 | - | - | 23.9 | 16.9 | 2.4 | 43.2 |
| 1 SEP | 1179 | 161 | - | - | - | 9.1 | 1.3 | 10.4 |
| 1 OCT | 1278 | 160 | - | - | - | - | 2.4 | 2.4 |
| 1 NOV | 1373 | 158 | - | - | - | - | - | - |
| 1 DEC | 1345 | 157 | - | - | - | - | - | - |

Modeling Dam Operation

Dams were located in the Cabuyal River at 0.2 km, 6.2 km and 15.2 km flow length from the watershed outlet. These locations were chosen because the immediate catchment area of the river at these locations—not including the catchment area of any upstream dams—were each about 1/3rd of the Cabuyal River watershed (Figure 4-7B). The upper and middle dam primarily controlled river flow rates in the middle and lower parts of the watershed, whereas the lower dam was only used to control flow rates at the outlet.

The operation of dams was simulated by specifying just three types of parameters: (1) the dam's equilibrium fraction $FR_{ST,x,d}$, which controls the rate of water release from the dam,

(2) the minimum required flow rate at the dam, $V_{MIN,x,d}$ and (3) the maximum allowed flow rate at the dam, $V_{MAX,x,d}$. Although these parameters could have been varied over time, they were set to a constant value all year (Table 4-8). Constant values simplified the parameterization of the model and were considered sufficient to meet the two objectives. Simulation results in Chapter 3 showed that the river flow rate depends on the catchment area in an almost linear fashion. Therefore, the minimum and maximum flow rates were chosen as, respectively, 100%, 66% and 33% of the desired flow rate at the watershed outlet.

Each dam had a storage capacity of 1 million $m^3$. The equilibrium storage in each dam was set to 300,000 $m^3$ ($ST_{MAX,s} \cdot FR_{ST,x}$). Storage in the dam was kept at this level whenever river flows were in between the minimum required flow and the maximum allowed flow. Thus, at equilibrium level, each dam could release up to 300,000 $m^3$ water to sustain the minimum flow of 400 L/s at the watershed, and store an additional 700,000 $m^3$ water whenever flow rates exceeded the maximum allowed flow rate of 1,500 L/s.

Table 4-8. Parameter settings for three dams. The same values were used every day.

| Location Dam | Storage Capacity ($ST_{MAX,s}$, $m^3$) | Water Release ($FR_{ST,x}$, -) | Minimum Flow ($V_{MIN,x}$, L/s) | Maximum Flow ($V_{MAX,x}$, L/s) |
|---|---|---|---|---|
| Lower dam | 1,000,000 | 0.3 | 400 | 1,500 |
| Middle dam | 1,000,000 | 0.3 | 255 [1] | 1,000 |
| Upper dam | 1,000,000 | 0.3 | 120 [1] | 500 |

[1] These values are slightly lower than 66% and 33% of the highest value to account for the fact that much water is used during dry period upstream from these dams.

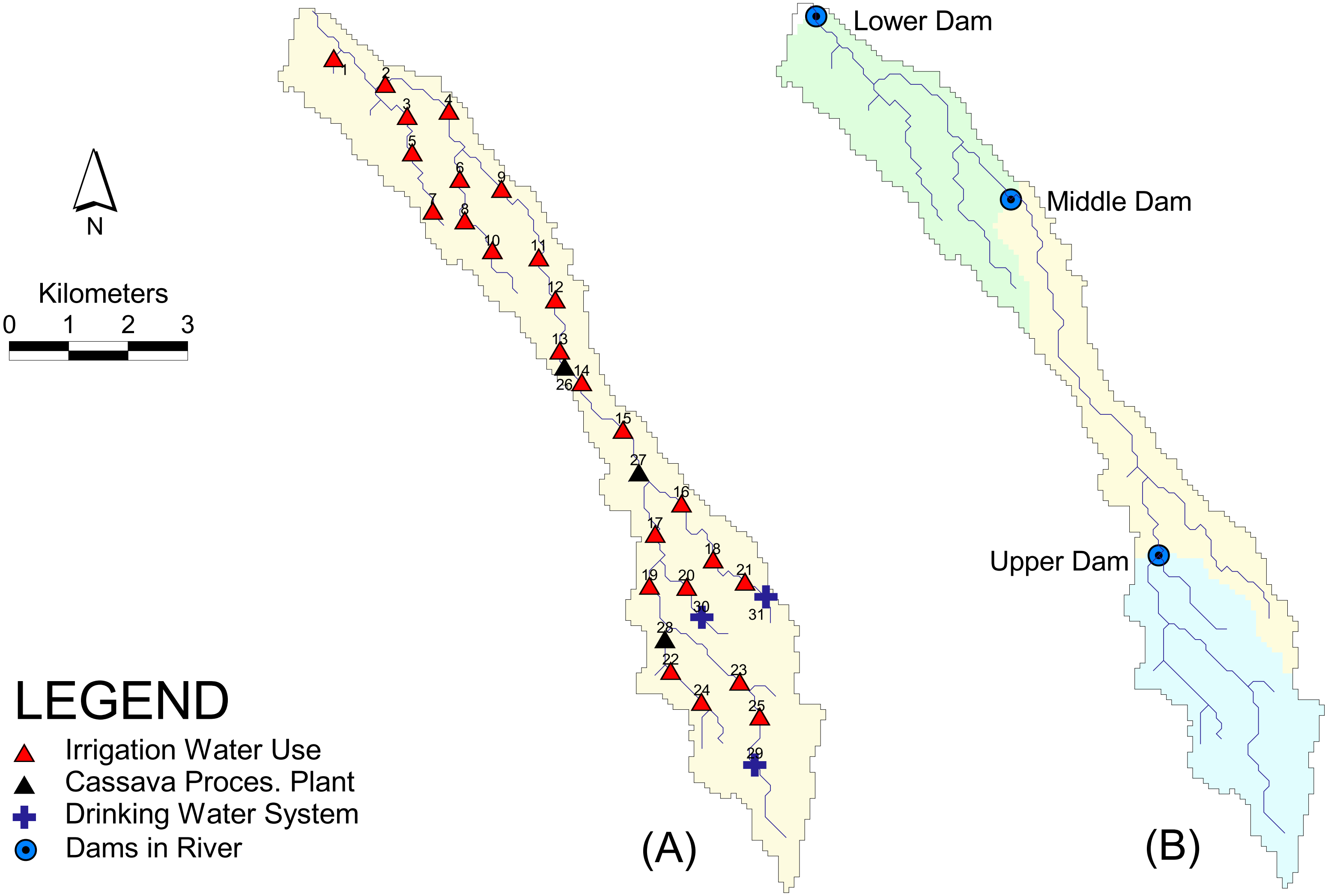



Figure 4-7. Simulated locations in the Cabuyal River watershed where water use takes place or dams are located. a) locations where water is extracted; b) dams. The immediate catchment areas of each dam, not including those of any upstream dams, are colored differently.

Results and Discussion

## Classifying Water Availability

Figures 4-7 through 4-10 show the simulated water availability (before water use and impedance by dams) from 1994 through 1997. In general, water availability was *low* from July through October, and it was *very low* during all or part of September and October. Water availability remained low until mid November in 1994, mid October in 1995, end of October in 1996 and till early November in 1997. This was about a month later than usual. The longest period (two months) of continuous very low water availability occurred during 1996.

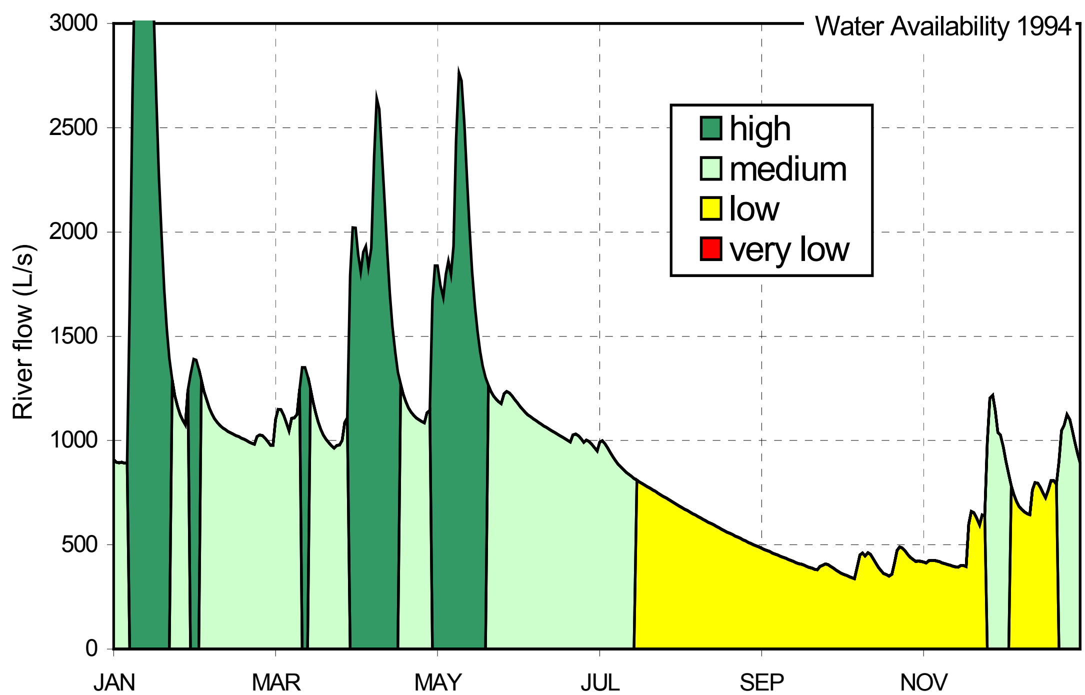



Figure 4-8. Classification of water availability in the Cabuyal River watershed in 1994, without water use and impedance by dams.

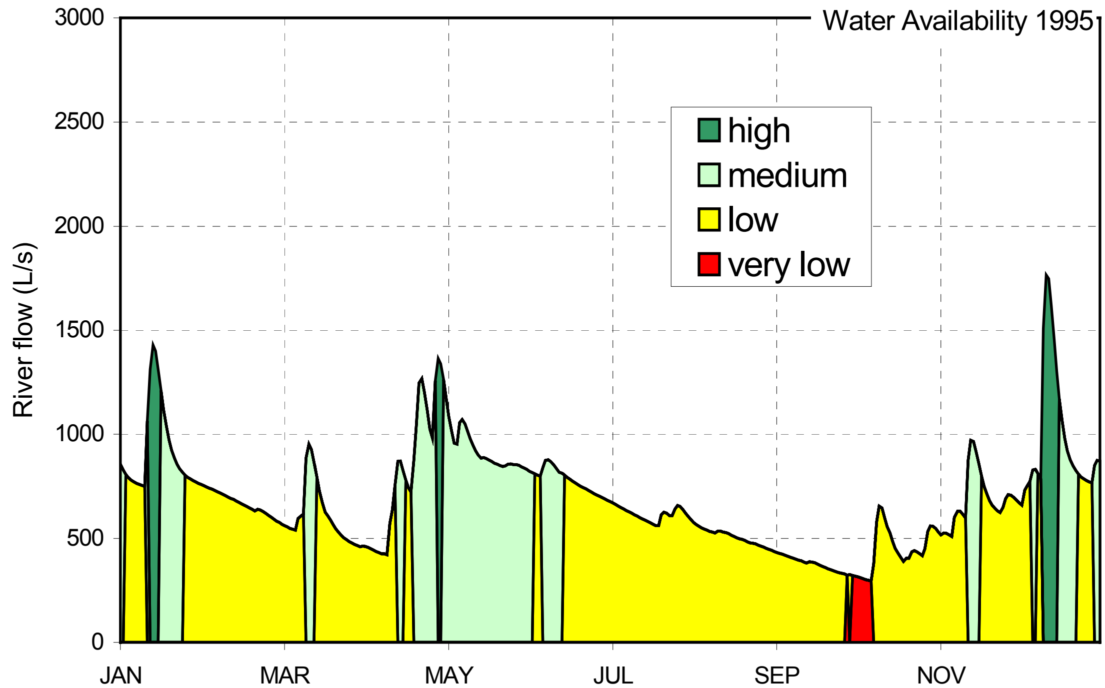



Figure 4-9. Classification of water availability in the Cabuyal River watershed in 1995, without water use and impedance by dams.

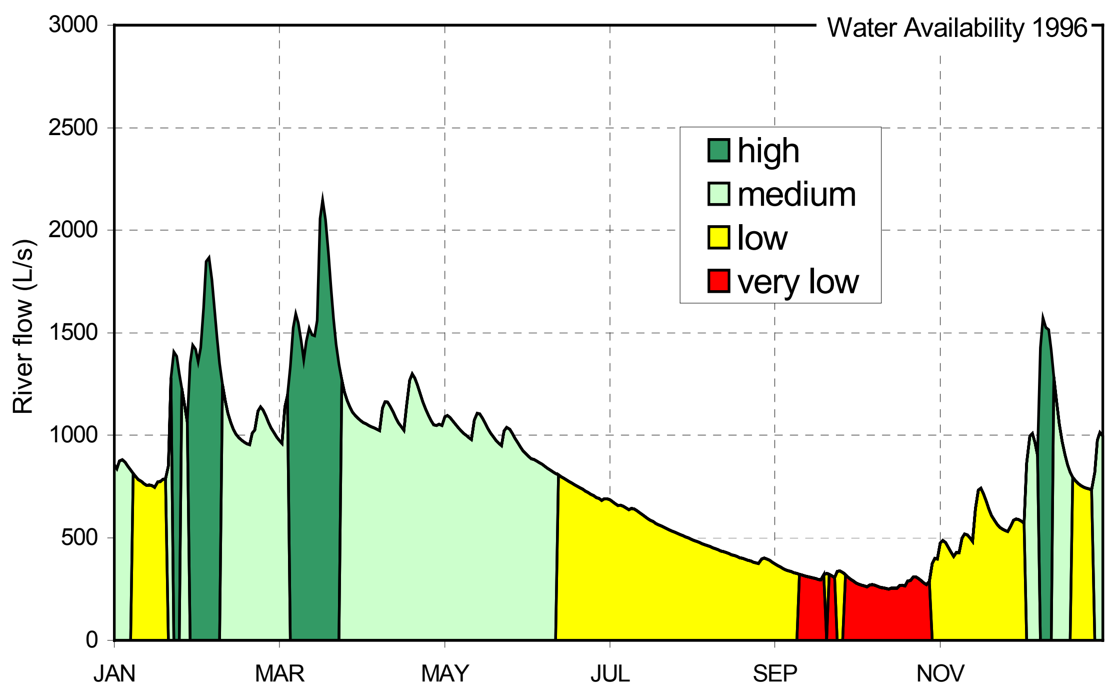



Figure 4-10. Classification of water availability in the Cabuyal River watershed in 1996, without water use and impedance by dams.

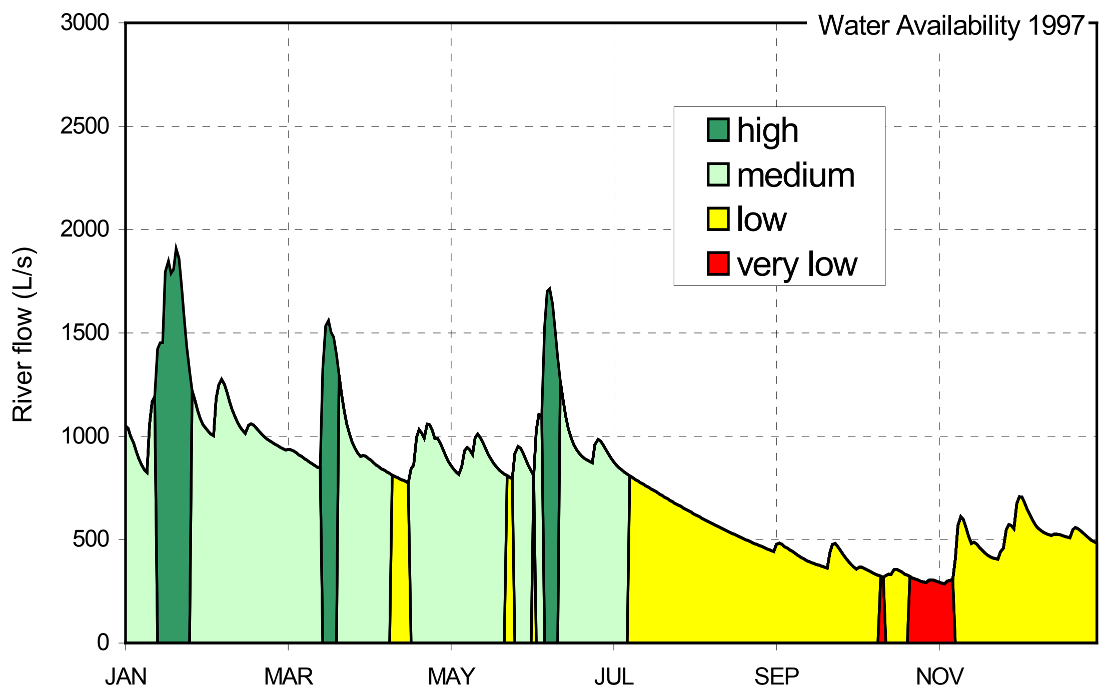



Figure 4-11. Classification of water availability in the Cabuyal River watershed in 1997, without water use and impedance by dams.

<u>Stream Flow After Water Use</u>

Figure 4-12 shows the simulated river flow rate at the water outlet after water use (but without the impedance by dams), as well as the change in river flow rate due to water use. The difference in y-direction between both curves is the gross water supply, which was shown in Figures 4-8 through 4-11. The lowest level of change in river flow rate occurred from October through May in every year. During this period there was only domestic and industrial water use at a combined rate of 1,633 $m^3d^{-1}$ (18.9 L/s).

Figure 4-13 shows the percentage of simulated river flow that was used. In Chapter 1 it was explained that one can consider water availability very low and a primary constraint to life if more than 40% of the available water resources are used (Seckler et al., 1998). Clearly, this was never the case in the Cabuyal River watershed during the years 1994-1997. The reason for the fact that water shortages did occur during the dry period in those years may be related to an inefficient allocation of the extracted water and the illegal use of large amounts of irrigation water from the drinking water system. These aspects were not accounted for during this simulation analysis. Figure 4-13 shows the actual water use strangely dropped during two weeks in October 1997, after which is increases again for a while. The cause for this temporary reduction in water use was that the flow rate of the Cabuyal River in the upper part of the watershed became very low and, consequently, insufficient to supply water to the main Laguna-Pescador drinking water system at the usual rate of 1,296 $m^3d^{-1}$ (15 L/s).

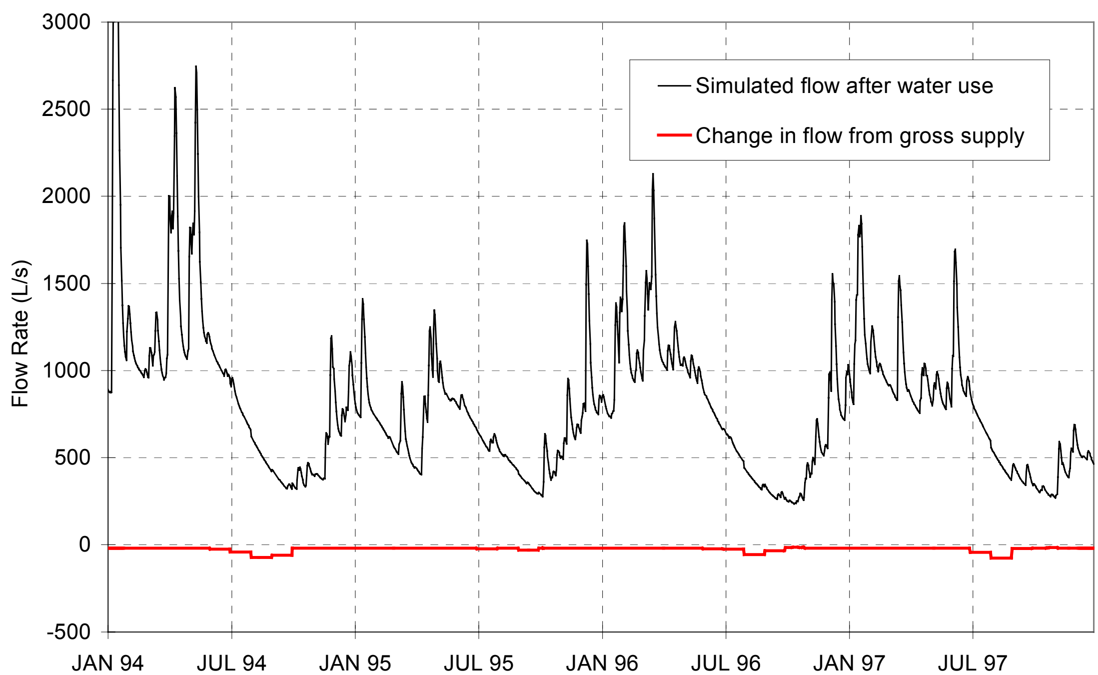



Figure 4-12. Simulated river flow at the watershed outlet after water use, and change in river flow from the gross supply due to water use, for the period 1994-1997.

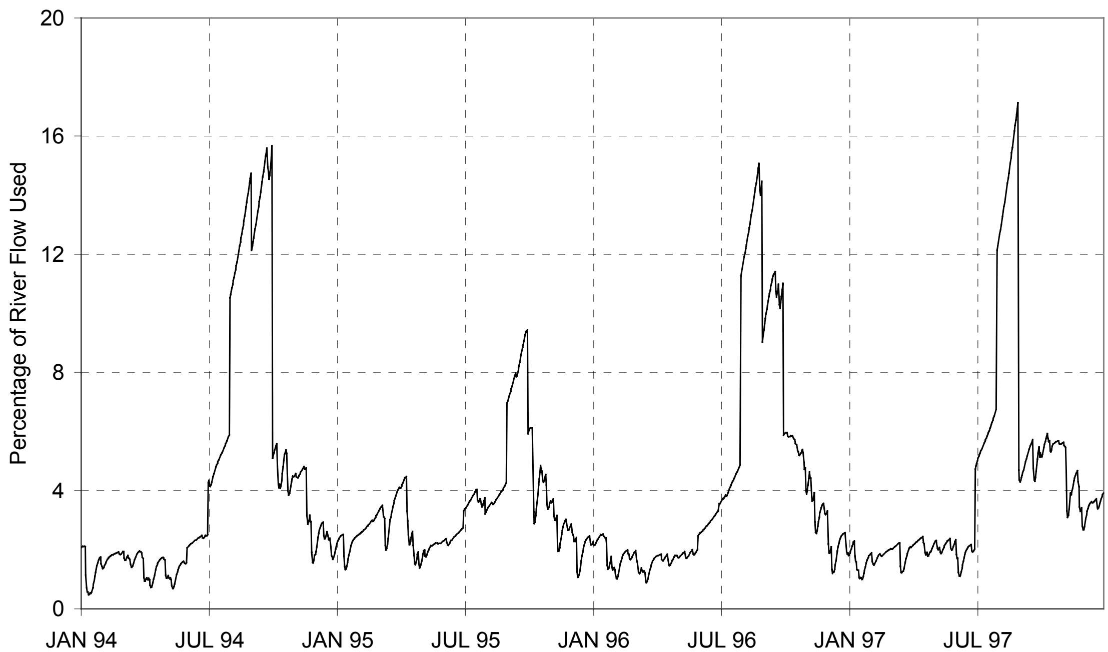



Figure 4-13. Simulated percentage of river flow that was extracted for domestic, industrial and agricultural uses, for the period 1994-1997.

Figure 4-14 shows the reduction in river flow due to water use at different distances from the watershed outlet. The top curve applies to a day without any irrigation water use, which was any day from October through May in any year. Water was then only used for domestic and industrial use at a combined rate of 1,633 $m^3d^{-1}$ (18.9 L/s). This rate corresponds to the point where the curve crosses the Y-axis. The bottom curve applies to any day in August 1997, when irrigation water use was highest. Total water use was then 6,633 $m^3d^{-1}$ (76.8 L/s). The jumps in the curves, representing a sudden decrease in the river flow rate, occurred at water extraction locations or where a smaller stream merged into the Cabuyal River. The reduction in river flow is cumulative along the flow path in downstream direction, clearly demonstrating that water availability in downstream communities is affected by water use in upstream communities.

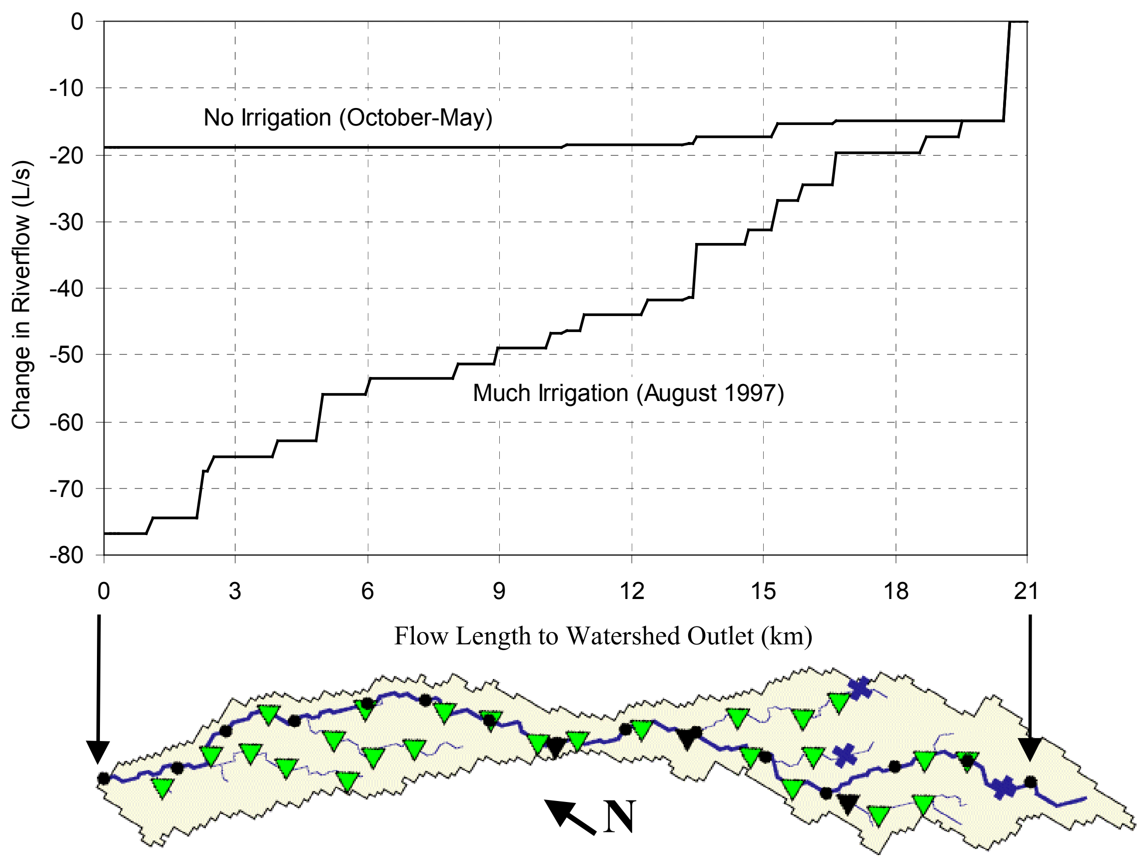



Figure 4-14. Simulated change in river flow rate due to water use, as a function of flow length to the watershed outlet, for a day without irrigation water use (every day from October through May) and for a day with the highest occurring irrigation water use (every day in August 1997). The flow length between the black dots is 1.5 km.

Table 4-9 gives the cumulative reduction in the river flow rate for 31 water extraction locations, for the day without irrigation and the day with much irrigation in August 1997. The location ID# correspond to those indicated in Figure 4-7A. Locations #1-25 is where irrigation water is used, locations #26-28 are cassava processing plants and locations #29-31 are the intakes of the drinking water systems. The reduction in river flow rate at the outlet is the sum of the reduction in stream flow at locations #1, #2 and #3.

Table 4-9. Cumulative reduction in stream flow rate at the 31 water extraction locations, for a day without irrigation (October through May) and a day with the highest irrigation water use (every day in August 1997). The location ID numbers correspond to those in Figure 4-7A.

| ID# | Without irrigation | Much Irrigation | ID# | Without Irrigation | Much Irrigation |
|---|---|---|---|---|---|
| | ----------- L/s ------------- | | | ----------- L/s ------------- | |
| 1 | 0.00 | 2.32 | 17 | 17.30 | 33.51 |
| 2 | 18.90 | 67.52 | 18 | 1.00 | 5.63 |
| 3 | 0.00 | 6.94 | 19 | 15.30 | 26.88 |
| 4 | 18.90 | 65.20 | 20 | 2.00 | 4.32 |
| 5 | 0.00 | 4.63 | 21 | 1.00 | 3.32 |
| 6 | 0.00 | 6.95 | 22 | 0.00 | 4.63 |
| 7 | 0.00 | 2.32 | 23 | 15.00 | 19.63 |
| 8 | 0.00 | 4.63 | 24 | 0.00 | 2.32 |
| 9 | 18.90 | 55.94 | 25 | 15.00 | 17.32 |
| 10 | 0.00 | 2.32 | 26 | 18.90 | 46.68 |
| 11 | 18.90 | 53.63 | 27 | 18.60 | 41.75 |
| 12 | 18.90 | 51.31 | 28 | 0.30 | 4.93 |
| 13 | 18.90 | 49.00 | 29 | 15.00 | 15.00 |
| 14 | 18.60 | 46.38 | 30 | 2.00 | 2.00 |
| 15 | 18.60 | 44.07 | 31 | 1.00 | 1.00 |
| 16 | 1.00 | 7.95 | OUTLET | 18.90 | 76.78 |

Effects of Dams in the River

Controlling river flow

Figure 4-15 shows the simulated river flow at the watershed outlet with the three dams. The major difference with the "unregulated" river flow is that the flow rate never dropped below 400 L/s and never exceeded 1,500 L/s.

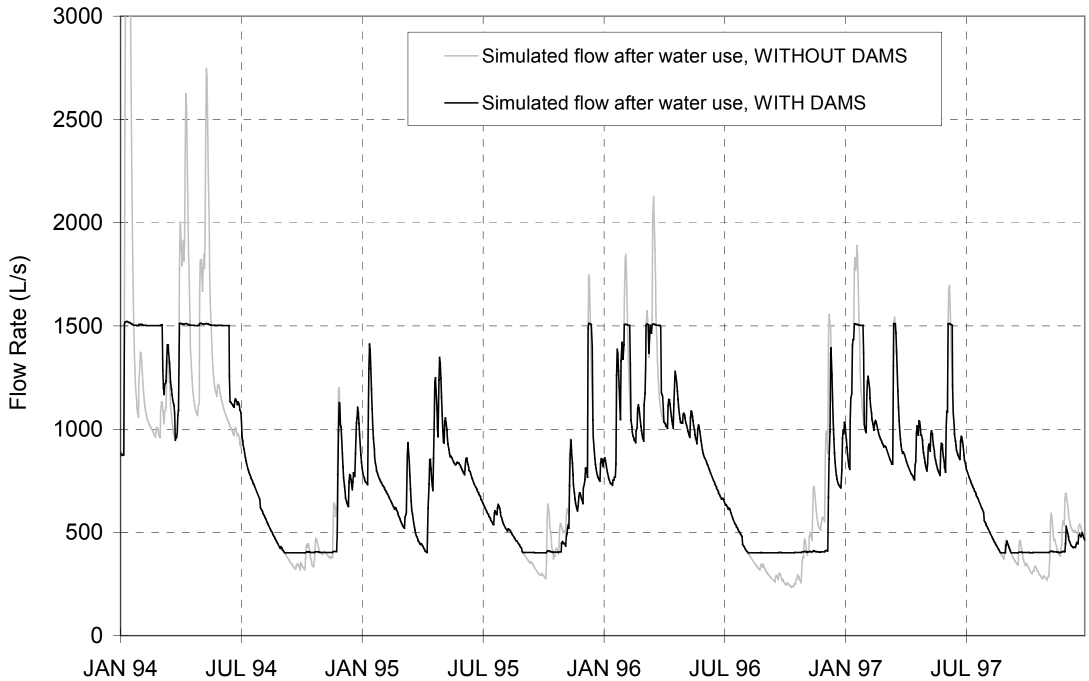



Figure 4-15. Simulated flow rate at the outlet of the Cabuyal River, after water use and with three dams that controlled the flow rate, for the period 1994-1997.

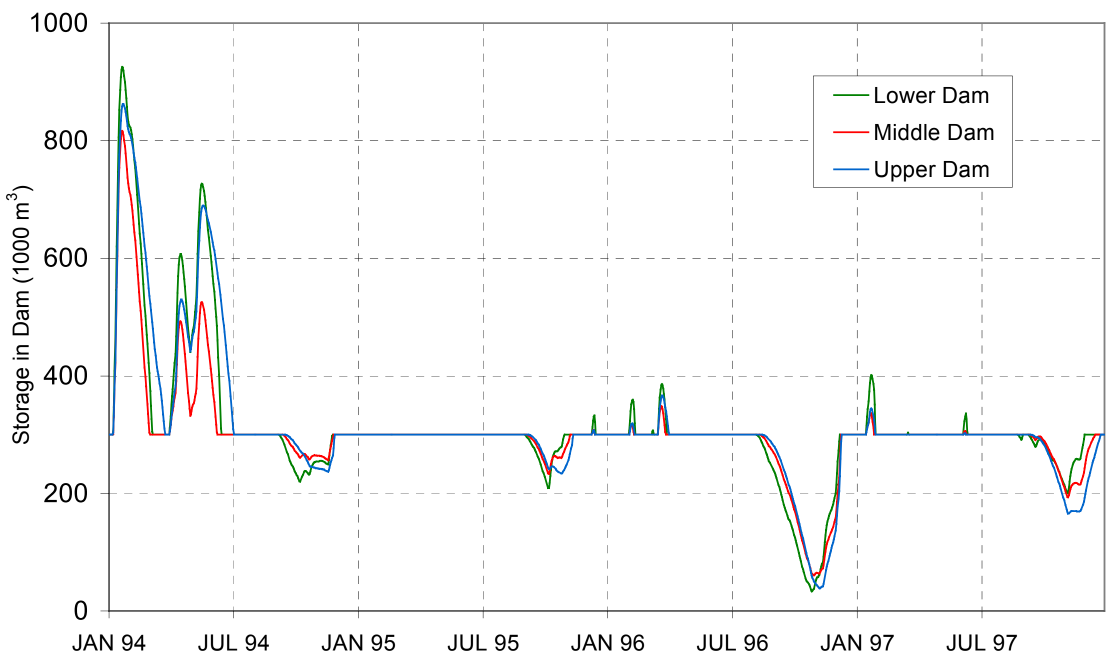



Figure 4-16. Simulated amount of water stored in each dam for the period 1994-1997. The equilibrium storage was set to 30% of the maximum storage capacity.

Figure 4-16 shows the amount of water stored in the dams during the 4-year period. The equilibrium level of storage was 300,000 $m^3$ in each dam. Storage increased at days with a flow rate higher than the maximum allowed rate. Storage decreased at the end of the dry period to sustain the minimum required flow rate. Storage never reached the capacity of the dams and none of the dams ever ran empty. The dams' capacities and equilibrium levels of storage were appropriately chosen such that the objectives of the dams were met at any time.

Figure 4-17 demonstrates the effect the dams had on river flow in different parts of the watershed. Curve A indicates the simulated river flow rate after water use on 27 March 1996, if no dams were present. The river flow rate (2,128 L/s) was higher than the maximum allowed flow rate (1,500 L/s). Curve B shows the river flow rate corrected by dams. Dams reduced the river flow rate to the minimum required flow at their locations. Notice that an upward jump in curves A and B indicates that a secondary stream merged with the Cabuyal River, whereas a downward jump indicates a reduction in stream flow rate caused by a dam. Curve C indicates the simulated river flow rate after water use on 13 October 1996, if no dams were present. The river flow rate (234 L/s) was lower than the minimum required flow rate (400 L/s). Curve D shows the river flow rate corrected by dams. Dams released some water to sustain the minimum required flow rates at their locations.

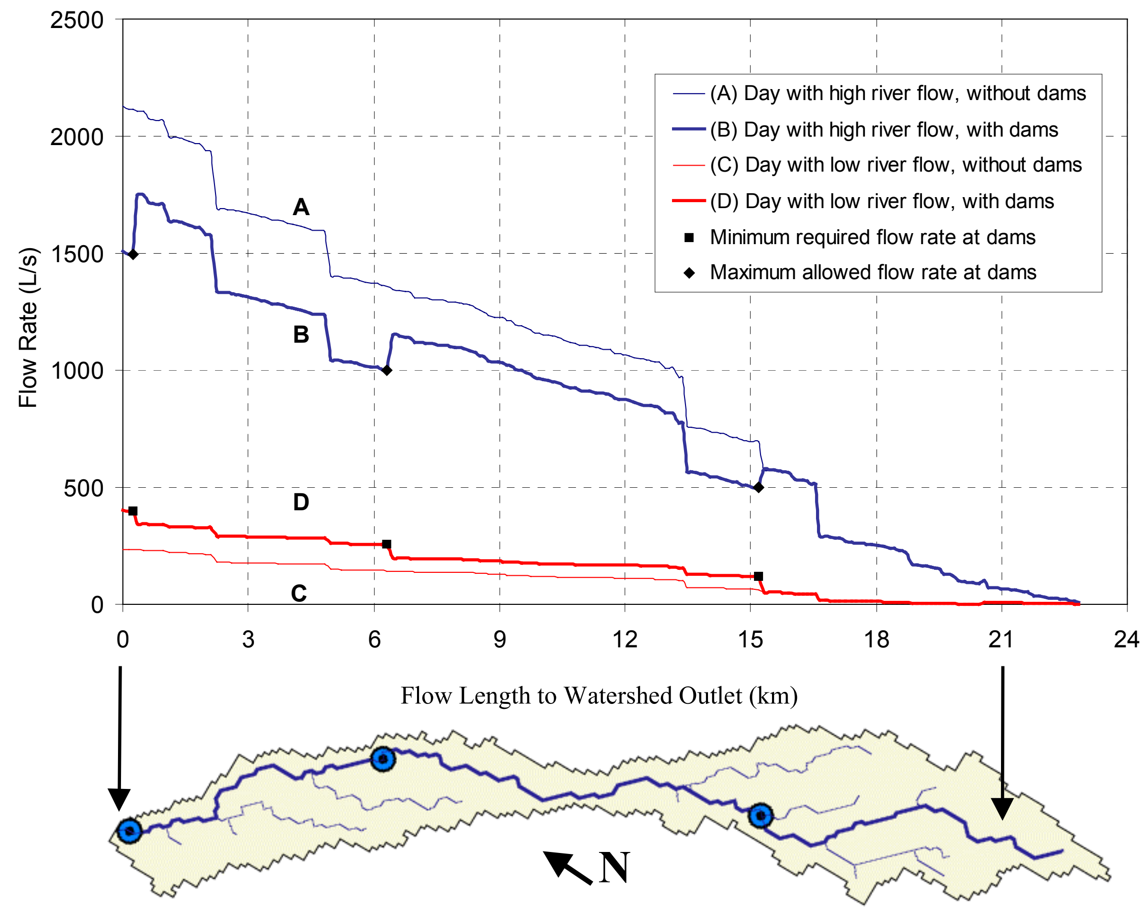



Figure 4-17. Simulated river flow rate after water use and with dams, as a function of flow length to the watershed outlet, for a day (27 March 1996) with a river flow rate higher than the maximum allowed flow rate, and for a day (13 October 1996) with a river flow rate below the minimum required flow rate.

Minimum required dam capacities

Figure 4-16 indicated that most of the capacity of the dams was not used during the greater part of the 4-year period, except during the first half of 1994 and the second half of 1996. I calculated the minimum combined capacity of the dams necessary to sustain a minimum river flow rate (Table 4-10). This was done for minimum flow thresholds of 300, 350, 400, 450 and 500 L/s at the watershed outlet. The dam capacities in Table 4-10 are the most conservative estimates, assuming that the equilibrium storage in the dams is maximal (dams are kept full whenever possible), i.e. with these capacities the dams could not be used to reduce peak flow rates. For the minimum required flow of 400 L/s, a combined storage capacity of 739,000 $m^3$ would have been sufficient. Thus, the equilibrium storage of 300,000 $m^3$ in each dam could have been decreased to as low as 246,000 $m^3$, assuming equal water release by the dams. The required dam capacities increase with higher minimum flow requirements.

Table 4-10. Combined storage capacity (filled) of the dams required to sustain minimum flow rates (after water use), for 5 different minimum flow rates, 1994 through 1997.

| Min. flow rate (L/s) | 300 | 350 | 400 | 450 | 500 |
|---|---|---|---|---|---|
| Year | ------------- Combined Capacity of Dams, in 1000 $m^3$ ------------ | | | | |
| 1994 | 0 | 31 | 187 | 483 | 861 |
| 1995 | 9 | 80 | 216 | 451 | 786 |
| 1996 | 144 | 400 | 739 | 1141 | 1586 |
| 1997 | 22 | 141 | 355 | 682 | 1119 |

I also calculated the combined capacity of the dams necessary to reduce the five largest peak flow rates in the period 1994-1997 (Table 4-11). This was done for maximum allowed flow rates of 1100, 1300, 1500, 1700 and 1900 L/s at the watershed outlet. The required dam capacities increase for lower maximum allowed flow rates. The dam capacities in Table 4-11 are the most conservative estimates, assuming that the equilibrium storage in the dams is minimal (dams are kept empty whenever possible), i.e. with these capacities the dams could not be used to sustain minimum flow rates. A combined storage capacity of 1.72 million $m^3$ would have been necessary to reduce the very high peak flow in January 1994 to 1500 L/s. Thus, the available capacity beyond the equilibrium storage of 700,000 $m^3$ in each dam could be reduced to 573,000 $m^3$, assuming equal water intake by the dams.

Table 4-11. Combined storage capacity (empty) of the three dams required to maintain a maximum flow rate, for 5 different maximum flow rates, 1994 through 1997.

| Max. flow rate (L/s) | 1100 | 1300 | 1500 | 1700 | 1900 |
|---|---|---|---|---|---|
| Time of peak flow | ------------- Combined Capacity of Dams, in 1000 $m^3$ ------------ | | | | |
| January 1994 | 2403 | 1985 | 1720 | 1483 | 1275 |
| April 1994 | 1395 | 1044 | 739 | 463 | 237 |
| May 1994 | 2922 | 1928 | 1068 | 454 | 278 |
| March 1996 | 838 | 475 | 214 | 110 | 43 |
| January 1997 | 612 | 368 | 187 | 61 | 0 |

If dams are used to control both minimum and maximum flow rates and the equilibrium storage in the dam is kept constant all year, then the capacities in Tables 4-10 and 4-11 must be added for the corresponding time periods. Assuming the 400 L/s minimum flow rate and the 1,500 L/s maximum flow rate, the required combined dam volume is for the entire four year period is 2.459 million $m^3$ (739,000 + 1,720,000). For the individual years 1994, 1995, 1995 and 1996 it is 1.907, 0.216, 0.953, and 0.543 million $m^3$, respectively. A lower dam capacity may be sufficient if the equilibrium storage is varied during the year. Storage should be kept low during the entire wet season (October-May), and should be increased near maximum storage at the beginning of the wet season (around June). This is a more efficient way of operating the dams, requiring less storage capacity, but achieving the same goals.

## Conclusions

According to the water availability classification that is used by some local planning agencies, simulated water availability in the Cabuyal River watershed was *low* or *very low* during about half of each simulated year. Nevertheless, there was ample water to meet estimated water demands throughout the entire simulation period, January 1994 through December 1997. The reduction in river flow due to water use never exceeded 16%, even not near the end of the dry seasons, when flow rates were lowest and total water demand high. If there were three dams with a storage capacity of 1 million $m^3$ each, a minimum flow rate of 350 L/s and a maximum flow rate of 1,500 could be sustained during that time period.

Current complains about reduced or insufficient water availability seem related to the fact that the drinking water systems are used as a source of irrigation water during the dry season, but they were not designed for this purpose. Irrigation water use from the drinking water systems was not simulated, however, from the data it was clear that estimated peak irrigation water requirements (up to 5,000 $m^3d^{-1}$ in August 1997) far exceeded the combined capacity of the drinking water systems (2,591 $m^3d^{-1}$) and could, therefore, impossibly be supplied by them. To solve these problems, one can consider increasing the capacity of the drinking water systems, building additional ones, or helping farmers exploit other sources of irrigation water, in particular by pumping it directly out of a stream.

# CHAPTER 5
# MODELING LAND USE CHANGE WITH STOCHASTIC RULES

## Introduction

The impetus for studies on land use changes comes from a variety of sources, including high pressures on the land due to increasing food demand and the need to meet environmental standards, the existence of powerful information technology, and emphasis on the long term and on future generations (Fresco, 1994). Various methodologies have been developed to describe the impact of biophysical and socioeconomic conditions on land use. Models have been developed to generate future land use patterns. Most models simulate land use using optimization techniques, extrapolation of past trends, or sets of logical rules.

Linear programming (LP) models are used for land use planning to determine an optimal land use pattern. The optimization objective is typically a representation of one or more tactical or strategic philosophies or policy implications, such as maximization of regional or farm income, household wealth, minimization of environmental pollution, maximization of resource use efficiency, and minimization of unemployment. LP models have been applied at continental, national, regional, and farm levels (Fresco et al., 1994).

An example of a LP model is the General Optimal Allocation of Land Use (GOAL) model. The Netherlands Scientific Council for Government Policy (1992) used this model to study regional distribution of land use for four different scenarios (free market and free trade; regional development; nature and landscape; environmental protection) for rural areas in the

European Community. GOAL is a complex model that can optimize land use to meet a combination of rural and agricultural policy goals, given a limited set of land use types and an exogenously defined demand for agricultural and forestry products (Rabbinge et al., 1994). Another optimization-based land use planning methodology is USTED (*Uso Sosteni-ble de Tierras En el Desarrollo*: Sustainable Land Use in Development) (Stoorvogel et al., 1995). It maximizes regional farm income subject to resource and sustainability constraints at various levels in the agricultural system, and was successfully used for regional and farm-level land use planning in Costa Rica (Jansen et al., 1997; Schipper et al., 1995).

Veldkamp and Fresco (1996a) argued that optimization models do not account for the actual conditions that caused land use changes in the past and may result in land use patterns that are not realistic. They introduced an alternative methodology to generate future land use patterns, called Conversion of Land Use and its Effects (CLUE). CLUE predicts future land use by looking at the interacting biophysical and human drivers factors that caused land use changes in the past and by extrapolating these relations into the near future (< 15 years). A comprehensive statistical analysis of the quantitative relationships between past and actual land use and potential driving forces underlies the land allocation procedure. CLUE allows one to analyze land use changes at different spatial aggregation levels (Veldkamp and Fresco, 1997b). The methodology was successfully applied to Costa Rica (Veldkamp and Fresco, 1996b, 1997b), Ecuador (de Koning, 1998) and China (Verburg et al., 1999).

Thornton and Jones (1997) developed a conceptual dynamic land use model to inves-tigate the feasibility of assembling land use models based on a simple set of rules and to investigate if land use evolves in a plausible fashion in response to changes in the driving factors. The rules account for the slope and drainage class of the land, quantity and price of seed and fertilizer, distance to roads, distance to market, transportation costs and household preferences. Seven possible land use types were considered: bean and maize by three input levels, and fallow. A transition matrix was defined to express the effects on yield of moving from one land use to another in successive time periods for a given combination of soil type, production input level and current crop. The model was applied to a hypothetical region consisting of 300 facets. Logical changes in land use patterns were simulated.

Rubiano (1998) developed a cellular automata (CA) land use change model. Cellular automata models consist of a one- or two-dimensional array of finite-state cells (automata). A set of rules defines how the state each cell changes based on its current state and the state of neighbor cells. The most striking feature of CA is that simple rules can result in complicated behavior (Hogeweg, 1988). Land use dynamics in Rubiano's model are partly based on rules and partly an extrapolation of past trends. Rubiano analyzed how changes in forest, scrub, and pasture occurred in the Cabuyal River watershed in Colombia with respect to distance to rivers, distance to roads and slope. He performed a detailed statistical analysis on land use maps of 1946, 1970 and 1989 (airphotography-based) to formulate a set of land use conversion rules for the CA model. The calibrated model was used to simulate land use changes in a another region with similar landscape characteristics, but for which no data on past land use were available. Land use changed in a plausible way.

This chapter describes a rule-based land use change model that generates land use patterns for any numbers of years in the future. Changes in land use are determined stochastically on a land unit basis for each year. The rate and direction of land use change depend on rules that account for specific characteristics about the location of a land unit in the landscape and relative tendencies to move from one land use type to another. This modeling approach shows similarity with the cellular automata model by Rubiano (1998), but it allows one to account for any number of spatial characteristics that are considered relevant in describing land use changes. Examples of such spatial characteristics include distance to nearest road, distance to houses, distance to cities, distance to streams, slope, elevation, erosion potential and land use of neighboring land units. The model was used to create a land use pattern for each of the three future scenarios for the Cabuyal River watershed for the year 2025. The scenarios are described in Appendix F.

## Materials and Methods

### Description of the Model

Land use (LU) changes are calculated on a land unit basis per time step. Assume an area containing a total of *X* land units, that there are currently *N* different LU types, *M* possible future LU types, and that a LU pattern for *T* years into the future must be generated (Fig. 5-1). It may be that *N*=*M*, however, it is possible that new LU types will be developed in the future or that some current LU types are nonexistent at some time in the future.

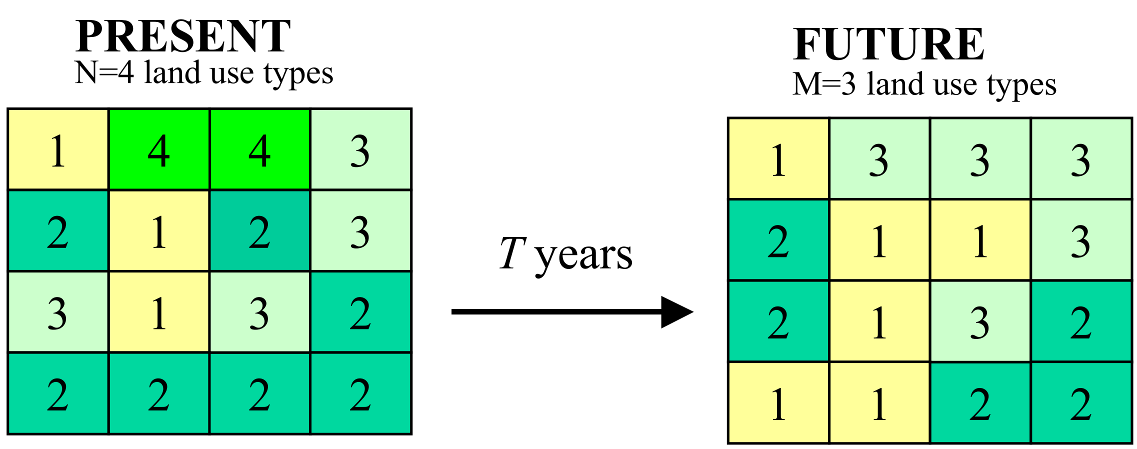



Figure 5-1. Schematic representation of a possible present and future land use pattern of a region that is divided into X=16 land units, with N=4 land use types at present and M=3 land use types after T years. The numbers 1, 2, 3 and 4 indicate different land use types.

Furthermore there are *R* different LU conversion rules that predominantly affect the direction of LU changes, and to a lesser extent the rate of change too. A land use conversion rule is a condition related to spatial characteristics that assigns non-equal relative tendencies to the conversion of a specific current LUC *n* type into all *M* different future LUC types. An example of a simple rule is that forest within 500 m of a road is deforested twice as fast as forest at a distance greater than 500 m from a road.

Each LU type *n* (with *n*=1..*N*) has a lookup table (Table 5-1). A row in such table is associated to a particular land use conversion rule *r* (with *r*=1..*R*). The numbers on row *r* are the relative tendencies $RT_{n,m,r}$ that LUC type *n* of a land unit *x* (with *x*=1,*X*) changes towards LUC type *m* (with *m*=1..*M*) during a time step (typically a year) if rule *r* applies. There are *N* lookup tables and each table has *M* columns and a maximum of *R* rows.

Table 5-1. Skeleton of a LU change lookup table for a land use type *n*=1. This table contains the applicable land use conversion rules *r* and relative tendencies $RT_{n,m,r}$ for changes from LU type *n*=1 towards every possible LUC type *m, with m=1..M*.

| | Description of rule | m=1 | m=2 | m=3 | …….. | m=M |
|---|---|---|---|---|---|---|
| r=1 | conversion rule #1 | $RT_{1,1,1}$ | $RT_{1,2,1}$ | $RT_{1,3,1}$ | …….. | $RT_{1,M,1}$ |
| r=2 | conversion rule #2 | $RT_{1,1,2}$ | $RT_{1,2,2}$ | $RT_{1,3,2}$ | …….. | $RT_{1,M,2}$ |
| ⋮ | ……………….. | …….. | …….. | …….. | …….. | …….. |
| r=R | conversion rule #R | $RT_{1,1,R}$ | $RT_{1,2,R}$ | $RT_{1,3,R}$ | …….. | $RT_{1,M,R}$ |

The overall relative tendency that LU type *n* changes towards LU type *m*, $RT_{OV,n,m}$, is calculated by multiplying the relative tendencies of all applicable rules. For each LU pair (*n,m*):

$$RT_{OV,n,m} = RT_{n,m,1} \cdot RT_{n,m,2} \cdot ..... \cdot RT_{n,m,R-1} \cdot RT_{n,m,R} \tag{5-1}$$

If a rule $r$ is not applicable to the conversion of LU type $n$, then the corresponding term $RT_{n,m,r}$ is not accounted for in Equation 5-1. If any single applicable rule $r$ excludes the conversion of LU type $n$ into $m$, i.e. $RT_{n,m,r} = 0$, then $RT_{OV,n,m} = 0$ regardless of the relative tendencies associated with other rules.

After applying Equation 5-1, the sum of the overall relative tendencies associated with the conversion of LU type $n$, $RT_{SUM,n}$, can be calculated. For each $n$=1..$N$,

$$RT_{SUM,n} = \sum_{m=1}^{M} RT_{OV,n,m}. \tag{5-2}$$

A value $RT_{SUM,n}$=0 for any $n$ implies that the combination of applicable rules prohibits the conversion of LU type $n$ into any $m$, which indicates an inconsistency or error in the set of rules in the probability table of LU type $n$. The actual probability that LU type $n$ changes towards LU type $m$, $P_{,n,m,}$ is calculated for each LU pair ($n,m$) as

$$P_{n,m} = RT_{OV,n,m} / RT_{SUM,n.} \tag{5-3}$$

Any rule $r$ with equal relative tendencies $RT_{n,m,r,,}$ with $m$=1..$M$, and $n$ and $r$ fixed (i.e. all numbers on a row in a lookup table are equal), is redundant because that rule does not affect the probabilities $P_{n,m}$. Equations 5-2 and 5-3 normalized the RT values such that for each LU type $n$,

$$\sum_{m=1}^{M} P_{n,m} = 1. \tag{5-4}$$

Next, the cumulative probabilities $P_{CUM,n,m}$ are calculated for each LUC pair ($n,m$),

$$P_{CUM,n,m} = P_{NORM,n,m} \qquad \text{for } m = 1 \quad \text{and} \qquad (5\text{-}5)$$

$$P_{CUM,n,m} = P_{NORM,n,m-1} + P_{NORM,n,m} \qquad \text{for } m = 2, M.$$

The last step in the analysis is the selection of a random number $RN_1$ from a uniform distribution between 0 and 1. Number $RN_1$ is compared with the annual probability of LU change, YRLUC ($yr^{-1}$). The value of YRLUC (also between 0 and 1) is specified at the start of the simulation and remains constant during the entire simulation period. YRLUC affects the overall rate of land use change. Land use change is not further considered if $RN_1 >$ YRLUC. A low value of YRLUC results thus in relatively few land use changes. If $RN_1 \leq$ YRLUC, a second random number $RN_2$ is drawn from the same uniform distribution to determine the new LU type *m*, which must meet the following requirement:

$$P_{CUM,n,m} < RN_2 \qquad \text{for } m = 1 \text{ and} \qquad (5\text{-}6)$$

$$P_{CUM,n,m-1} < RN_2 \leq P_{CUM,n,m} \qquad \text{for } m = 2, M.$$

Only one LU type *m* meets this requirement; $n$=$m$ is a valid result also. It means that the LU type changed towards itself, i.e. land use does not change. Thus, $RN_1 \leq$ YRLUC does not mean that the LU type actually changes. The actual probability that LU type *n* of any land unit *x* changes towards another LU type $m \neq n$ during any single year *t* is always equal to or less--never greater--than YRLUC. Equations 5-2 through 5-6 are evaluated for each land unit *x*, with $x$=1..$X$, and for each year *t*, with $t$=1..$T$.

The model was written in Fortran 77. All raster data are read and written as ARC/INFO grids in ASCII format. These raster input data include the initial LU pattern ($t$=0) and all spatial characteristics needed to evaluate the LU conversion rules. The relative tendencies are read from comma-delimited ASCII files which have the same format as Table 5-1 (each lookup table as a separate file). Values for *T*, YRLUC and (optionally) the SEED of the random number generator are specified as command line arguments at the start of the simulation. If no SEED is specified, the program will automatically determine one based on the current time. Use of the same SEED allows regenerating the same series of LU patterns (only if YRLUC and relative tendencies remained unchanged). A new LU pattern is saved at every time $t$ ($t$=1..$T$) as an ARC/INFO grid in ASCII format. These grids can be directly imported and displayed in ARC/INFO or ArcView GIS software and were inputted to the SWBM model.

Example of the Calculation Methodology

A simple example is now given to illustrate the model logic and different calculation steps. The LUC conversion rules and relative tendencies of land use changes are based on data from Rubiano (1998). Rubiano identified three distinct LUC types in the Cabuyal River watershed: forest, scrub and pasture. He used four different *distance-to-road* classes (1-200 m, 200-400 m, 400-600 m, and >600 m) and also four different *distance-to-river* classes (1-100 m, 100-200 m, 200-300 m, and >300 m). To simplify this example, the first two classes as well as the last two classes were merged in both classifications. Thus, $R$=4.

The frequencies of LU conversions between forest, pasture and scrub from 1946 to 1970 were used as relative tendencies $TR_{n,m,r}$, where $n$=1 (forest) refers to Table 5-2, $n$=2 (pasture) to Table 5-3, $n$=3 (scrub) to Table 5-4, $m$ to the $m^{th}$ data column in each table and $r$ to the $r^{th}$ data row in each table. These conversion frequencies were based on an average of one change during a period of 24 years (1946-1970), thus YRLUC should be 1/24 (0.0416).

Here, I determine how land use changes for a single land unit over time, assuming that the land unit has a forest cover (*n*=1) on *t*=0, is farther than 400 m from a road (*r*=2) and farther than 200 m from a stream (*r*=4). The conversion frequencies from Table 5-2 were used as relative tendencies.

Table 5-2 Conversion frequencies from forest in 1946 towards forest, pasture and scrub in 1970, using a reduced set of conversion rules that accounted for distance to roads and rivers.

| Rules | Forest | Pasture | Scrub |
|---|---|---|---|
| Distance to road <= 400 m | 0.233 | 0.500 | 0.267 |
| Distance to road > 400 m | 0.071 | 0.858 | 0.071 |
| Distance to river <= 200 m | 0.103 | 0.517 | 0.371 |
| Distance to river > 200 m | 0.061 | 0.788 | 0.151 |

Source: Rubiano (1998)

Table 5-3. Conversion frequencies from pasture in 1946 towards forest, pasture and scrub in 1970, using a reduced set of conversion rules that accounted for distance to roads and rivers.

| Rules | Forest | Pasture | Scrub |
|---|---|---|---|
| Distance to road <= 400 m | 0.068 | 0.716 | 0.216 |
| Distance to road > 400 m | 0.071 | 0.866 | 0.063 |
| Distance to river <= 200 m | 0.058 | 0.744 | 0.198 |
| Distance to river > 200 m | 0.020 | 0.666 | 0.314 |

Source: Rubiano (1998)

Table 5-4. Conversion frequencies from scrub in 1946 towards forest, pasture and scrub in 1970, using a reduced set of conversion rules that accounted for distance to roads and rivers.

| Rules | Forest | Pasture | Scrub |
|---|---|---|---|
| Distance to road <= 400 m | 0.085 | 0.439 | 0.476 |
| Distance to road > 400 m | 0.084 | 0.729 | 0.187 |
| Distance to river <= 200 m | 0.071 | 0.470 | 0.459 |
| Distance to river > 200 m | 0.000 | 0.699 | 0.301 |

Source: Rubiano (1998)

Table 5-5 shows the different steps to calculate the cumulative probabilities of change from *n*=1 towards *m*=1, *m*=2 and *m*=3. Table 5-6 shows the results when 3 years are simulated. Two random numbers ($RN_1$, $RN_2$) were drawn at each year. The land unit does not change at *t*=1 and *t*=2 because $RN_1$ is greater than YRLUC (0.0416). However, $RN_1$ is smaller than YRLUC at t=3. The direction of change is then determined by the value of $RN_2$. This value (0.6785) is between the commutative probabilities of forest (0.0063) and pasture (0.9845), so land use changes towards the latter (Eq. 5-6). Once land use has changed, the land conversion probabilities in Table 5-5 do not apply anymore. Before the simulation can be continued for *t*=4 and higher, the three calculation steps in Table 5-5 must be repeated for pasture (*n*=2), using relative tendencies from Table 5-3.

Table 5-5. Calculation of probabilities of conversion for forest (*n*=1) towards forest, pasture and scrub, for a land unit further than 400 m from a road and 200 m from a stream, based on Equations 5-2, 5-4 and 5-5.

| Calculation step | Forest (*m*=1) | Pasture (*m*=2) | Scrub (*m*=3) |
|---|---|---|---|
| 1. Overall relative tendencies, $RT_{OV,1,m}$ | 0.0043 | 0.6761 | 0.0107 |
| 2. Actual probability of change, $P_{,1,m}$ | 0.0063 | 0.9782 | 0.0155 |
| 3. Cumulative probabilities, $P_{CUM,1,m}$ | 0.0063 | 0.9845 | 1.0000 |

Table 5-6. Selection of random numbers and simulated land use for a 3-year period for a forested land unit that is further than 400 m from a road and 200 m from a stream.

| | | | ------------- Land Use------------- | | |
|---|---|---|---|---|---|
| Year (*t*) | $RN_1$ | $RN_2$ | Forest | Pasture | Scrub |
| 1 | 0.5322 | 0.1143 | X | | |
| 2 | 0.8013 | 0.2911 | X | | |
| 3 | 0.0398 | 0.6785 | | X | |

Model Parameterization for the Cabuyal River Watershed

Initial land use pattern

The initial LU data set for the Cabuyal River watershed was based on a classification of a Landsat TM image from 1989 (Langford and Bell, 1997). This classification consisted of 10 different LU types (Figure 3-7). If was difficult to create a logical and consistent set of conversion rules and 10 tables with relative tendencies because the differences between some LU types are small. The number of LU types was therefore reduced from ten to five by aggregating similar LU types (Table 5-7). The resulting five LU types are bare soil, pasture, scrub, forest and crops. These five LU types were also considered for any time in the future, thus, $N$=$M$=5.

Table 5-7. Aggregated land use/land cover (LUC) types and areas covered within the 3,246 ha Cabuyal River Watershed, after aggregation of a 1989 Landsat TM image classification.

| LUC type | Non-aggregated LUC types | Total Area (ha) | Area/person[1] (ha) |
|---|---|---|---|
| Bare Soil | No vegetation, Exposed soil | 393 | 0.170 |
| Pasture | Space pasture; Dense pasture | 1243 | 0.538 |
| Scrub | Bush Scrub | 797 | 0.346 |
| Forest | Young forest, Mature forest; Bamboo | 520 | 0.225 |
| Cropland | Coffee; Cropped land | 293 | 0.126 |

[1] Proportionally based on a total of 5,357 people living within the 7,525 ha administrative Cabuyal watershed.

Land use conversion rules

The following characteristics of the landscape in the Cabuyal River watershed were used to define LU conversion rules: (1) Euclidean distance to roads, (2) Euclidean distance to streams, (3) Euclidean distance to houses, (4) terrain slope, (5) elevation and (6) land use type of adjacent land units. All data sets were ARC/INFO grids with a resolution of 100 m.

Table 5-8 shows the frequency distribution of the first five spatial properties. These distributions will be different if data at another resolution were used. These five spatial characteristics were assumed constant throughout the entire simulation period $t$=1,$T$. In reality, distances to roads and houses may change over time due to changes in the population and the road network. This was not considered. The sixth characteristic—land use type of adjacent land units—changes each year as land use changes. The model calculated it on each year $t$ from the land use pattern at that time.

Table 5-8. Cumulative frequency distribution of five spatial characteristics in the Cabuyal River watershed, based 100 m resolution data and a total of 3,246 land units.

| | Distance to roads (m) | Distance to streams (m) | Distance to houses (m) | Slope (degrees) | Elevation (m) |
|---|---|---|---|---|---|
| 0% | 0 | 0 | 0 | 0.22 | 1265 |
| 10% | 141 | 100 | 141 | 2.89 | 1450 |
| 25% | 300 | 224 | 300 | 5.18 | 1513 |
| 33% | 361 | 300 | 361 | 6.22 | 1549 |
| 50% | 500 | 400 | 447 | 8.21 | 1674 |
| 66% | 600 | 448 | 566 | 10.98 | 1804 |
| 75% | 632 | 510 | 608 | 12.80 | 1887 |
| 90% | 707 | 583 | 670 | 17.40 | 2032 |
| 100% | 761 | 608 | 781 | 32.06 | 2176 |

Sources: Elevation and slope were based on the DEM in Fig. 3-5. Road and house data from 1995 were used. Streams were those on a typical dry day in the wet season in Fig. 3-13b.

A total of 14 LU conversion rules were defined (Table 5-9). Each conversion rule accounted for only one of these spatial characteristics and could be either *true* or *false* for a particular land unit. The conversion rules and the associated probabilities were partly based on Rubiano (1998), however, most of all they are based on assumptions about the possible affect of spatial attributes on changes from any LU type $n$ towards type $m$. The cutoff values used in rules 4 through 11 (500 m, 300 m, 400 m, and 10 degrees, respectively) were chosen near the median in the corresponding frequency distribution. The three elevation classes were chosen such that the watershed is divided into three similarly sized regions (lower zone 1039 ha, middle zone 1132 ha and upper zone 1075 ha)

Table 5-9. Land use (LU) conversion rules for the Cabuyal River watershed.

| | | | |
|---|---|---|---|
| 1. | 0, 1 or 2 adjacent land units same LU | 8. | Distance to house ≤ 400 m |
| 2. | 3, 4 or 5 adjacent land units same LU | 9. | Distance to house > 400 m |
| 3. | 6, 7 or 8 adjacent land units same LU | 10. | Slope ≤ 10 degrees |
| 4. | Distance to roads ≤ 500 m | 11. | Slope > 10 degrees |
| 5. | Distance to roads > 500 m | 12. | Elevation < 1525 m (lower zone) |
| 6. | Distance to streams ≤ 300 m | 13. | Elevation ≤ 1725 m (middle zone) |
| 7. | Distance to streams > 300 m | 14. | Elevation > 1725 m (upper zone) |

Relative tendencies of LU change

The land use change model was used to generate a future land use pattern for three contrasting scenarios for the Cabuyal River watershed in the year 2025. These scenarios are referred to as the *Corporate Farming* scenario, *Ecological Watershed* scenario and the *Business as Usual* scenario (Appendix F). Hence, three different sets of lookup tables with relative tendencies of LU change were created. Each set consists of 5 tables—one for each land use type. The same set of land use conversion rules (Table 5-9) was used in each table.

Tables 5-10 through 5-14 give the conversion probabilities for the *Corporate Farming* scenario, Tables 5-15 through 5-19 for the *Ecological Watershed* scenario and Tables 5-20 through 5-24 for the *Business as Usual* scenario. A row without numbers in a table—which corresponds to the set relative tendencies {1, 1, 1, 1, 1}—means that the particular rule was not considered relevant for LU change from that particular LU type. The lowest value on each data row was set to 1, and all other values were specified relative to 1.

Unlike in the earlier example, a value of YRLUC could not be calculated because land conversion rules and relative tendencies were based on assumptions rather than analysis of actual data. After some trial-and-error simulation runs, YRLUC was set to 0.05.

## Overview of Analyses

First, land use was simulated for 36 years (1989-2025) to create a plausible future land use pattern for each of the three scenarios. A longer period of 100 years (1989-2089) was also simulated with the aim to demonstrate the long-term behavior of the model and to investigate whether the land use distribution would reach some equilibrium. The number of times that the LU type at any particular land unit could change during the simulation period was not restricted in any way, i.e. it could change 0, 1 or more times, up to each year.

Secondly, the sensitivity of the model to three different types of input parameters was analyzed. These sensitivity analyses were only performed using the results of the standard *Business as Usual* simulation as a reference.

Random generator SEED. The first parameter was the SEED for the random generator function that is used in the Fortran program. A different SEED changes the starting point of the random generator function (Microsoft Corporation, 1991), resulting in a different sequence of random numbers $RN_1$ and $RN_2$ and, consequently, in different results. A total of 100 replicates of the 36-year simulation run were made with different, SEEDs.

Relative tendencies. The second type of parameter was the relative tendency $RT_{n,m,r}$. For each LU type separately, I analyzed the effect of a 50% higher relative tendency for changes towards that LU type (including the possibility that the LU type changes towards itself, i.e. it remains the same). The 50% increase in relative tendency towards a particular LU type was implemented by adding an additional rule that is always true (slope ≤ 90 degrees) to Tables 5-20 through 5-24. The relative tendencies associated with the new rule were {1.5, 1, 1, 1, 1} for bare soil, {1, 1.5, 1, 1, 1} for pasture, {1, 1, 1.5, 1, 1} for scrub, {1, 1, 1, 1.5, 1} for forest and {1, 1, 1, 1, 1.5} for crops. The relative tendencies associated with other rules were not changed. Changes were made in the five tables only for one LU type at the time. For each LU type, 100 replicates of a 100-year simulation run were made with different, automatically determined SEED values.

Note that column-wise increasing all relative tendencies of the existing rules with 50%—rather than adding the single additional rule— is not the correct way to conduct this sensitivity analysis. Because relative tendencies are multiplied (Eq. 5-1), the overall increase in relative tendency towards a particular LU type would be greater, up to a factor $1.5^6$ if the maximum of six conversion rules apply. Consequently, land use would change much stronger towards one particular LU type, which could result (near) elimination of the other LU types.

<u>Parameter YRLUC</u>. The third parameter was YRLUC, which controls the speed with which LU changes occur. A 100-year period was simulated using YRLUC values of 0.05 (the standard simulation), 0.10 and 0.15. The same SEED value was used for these simulations.

Table 5-10. Relative tendencies for conversion from bare soil, Corporate Farming scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 0 | 1 | 1 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 4 | 1 | 1 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 6 | 1 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 1 | 2 | 1 | 1 | 2 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 2 | 1 | 1 | 2 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 2 | 1 | 1 | 1 | 1 |
| 11 | Slope > 10 degrees | 6 | 1 | 1 | 1 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A land unit with bare soil is more likely to remain bare soil if many adjacent land units are bare soil as well. Small and isolated areas of bare soil will be improved and change towards any other land use. Bare soil close to houses and streams is more likely to be converted into cropping land or pasture rather than scrub or forest. Bare soil on steep slopes is likely to remain bare soil because there is little incentive to improve such areas for corporate farming.

Table 5-11. Relative tendencies for conversion from pasture, Corporate Farming scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 2 | 1 | 2 | 2 | 2 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 4 | 1 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 6 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 2 | 1 | 1 | 1 |
| 5 | Distance to roads > 500 m | 1 | 2 | 0 | 2 | 1 |
| 6 | Distance to streams ≤ 400 m | - | - | - | - | - |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 2 | 2 | 2 | 2 | 1 |
| 11 | Slope > 10 degrees | 1 | 1 | 1 | 1 | 0 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A land unit with pasture is more likely to remain pasture if many adjacent land units have pasture as well. This promotes clustering of pasture. Pasture close to roads has the greatest chance to remain pasture, whereas at greater distance from roads pasture converts more likely into forest and cannot convert to scrub. Pasture does not change towards cropland on steep slopes.

Table 5-12. Relative tendencies for conversion from scrub, Corporate Farming scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 2 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 4 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 6 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | 1 | 2 | 1 | 1 | 1 |
| 6 | Distance to streams ≤ 400 m | 2 | 2 | 4 | 2 | 1 |
| 7 | Distance to streams > 400 m | 2 | 2 | 2 | 0 | 1 |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | - | - | - | - | - |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A scrub land unit is more likely to remain scrub if many adjacent land units are scrub as well. Scrub at greater distance from roads is more likely to change to pasture than to any other land use types. Conversion from scrub into cropland is fairly rare. Scrub close to streams is most likely to remain scrub and least likely to change towards cropland. Scrub at great distance from streams does not change towards forest.

Table 5-13. Relative tendencies for conversion from forest, Corporate Farming scenario.

| | | ------------------ Land Use ------------------ | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 1 | 0 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 4 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 6 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 1 | 1 | 1 | 2 |
| 5 | Distance to roads > 500 m | 1 | 1 | 1 | 2 | 1 |
| 6 | Distance to streams ≤ 400 m | - | - | - | - | - |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 3 | 3 | 3 | 1 | 3 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 0 | 1 | 0 | 1 | 2 |
| 11 | Slope > 10 degrees | 1 | 1 | 1 | 3 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | 1 | 1 | 1 | 1 | 2 |
| 14 | Elevation > 1725 m | 1 | 1 | 1 | 3 | 1 |

Assumptions: A forest land unit is more likely to remain forest if many adjacent land units are forest as well. Isolated forest is always cut. Forest close to houses is also likely to be cut. However, forest on steeper slopes and in the upper part of the watershed is generally preserved. Forest is more likely to change to pasture or cropland rather than scrub or fallow. Forest close to roads is most likely to change into cropland. Forest in relatively flat areas does not change towards are soil or scrub because these areas are very valuable for crop production.

Table 5-14. Relative tendencies for conversion from cropland, Corporate Farming scenario.

| | | Land Use | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | - | - | - | - | - |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 1 | 3 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 1 | 6 |
| 4 | Distance to roads ≤ 500 m | 1 | 1 | 1 | 1 | 3 |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | - | - | - | - | - |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 1 | 1 | 1 | 3 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | - | - | - | - | - |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: Cropland is very valuable asset and corporate farms use the same area of cropland for many years. Therefore, cropland has a high probability to remain cropland, particularly if many adjacent land units are cropland as well or of if is close to houses and roads. The latter facilitate good access for further transport of agricultural goods.

Table 5-15. Relative tendencies for conversion from bare soil, Ecological Watershed scenario.

| | | Land Use | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 0 | 1 | 1 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 2 | 2 | 2 | 2 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 2 | 1 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 1 | 2 | 0 | 3 | 1 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 2 | 1 | 3 | 2 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 1 | 2 | 1 | 4 | 1 |
| 11 | Slope > 10 degrees | 1 | 2 | 1 | 6 | 0 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: Land improvements are very important in the Ecological Watershed scenario. Therefore, bare soil is very likely to change towards any other land us type. On steep slopes it can change best towards forest or pasture to provide good cover and minimize risk for erosion. Bare soil close to streams is most likely to change towards into forest or pasture to create vegetation buffer zones.

Table 5-16. Relative tendencies for conversion from pasture, Ecological Watershed scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 2 | 1 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 4 | 1 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 6 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 2 | 1 | 2 | 1 |
| 5 | Distance to roads > 500 m | 1 | 2 | 0 | 2 | 1 |
| 6 | Distance to streams ≤ 400 m | - | - | - | - | - |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 0 | 4 | 2 | 2 | 1 |
| 11 | Slope > 10 degrees | 0 | 2 | 1 | 1 | 0 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: Pasture is likely to remain pasture if many adjacent land units have pasture cover as well. This promotes clustering of pasture. Close to roads pasture has the greatest chance to remain pasture or change towards forest. Pasture is unlikely to change into crop-land, particularly if slopes are steep. Pasture cannot change towards bare soil.

Table 5-17. Relative tendencies for conversion from scrub, Ecological Watershed scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 2 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 4 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 6 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | 1 | 2 | 1 | 1 | 1 |
| 6 | Distance to streams ≤ 400 m | 2 | 2 | 4 | 4 | 1 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | - | - | - | - | - |
| 12 | Elevation < 1525 m | 1 | 1 | 1 | 2 | 1 |
| 13 | Elevation 1525 - 1725 m | 1 | 1 | 1 | 2 | 1 |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: Scrub is likely to stay the same if most adjacent land units have scrub as well. If scrub changes, the direction will most likely be toward pasture or forest. Scrub close to streams and in the middle and upper parts of the watershed are most likely to change towards forest.

Table 5-18. Relative tendencies for conversion from forest, Ecological Watershed scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 1 | 6 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 9 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 12 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 1 | 1 | 1 | 2 |
| 5 | Distance to roads > 500 m | 1 | 1 | 1 | 3 | 1 |
| 6 | Distance to streams ≤ 400 m | 1 | 1 | 1 | 4 | 2 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 2 | 2 | 1 | 3 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | 0 | 1 | 1 | 1 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: Forest is the most protected land use type and changes little as compared to the other land use types. Any forest cut close to roads and streams is most likely to change towards cropland. Forest on steep slopes can never change into bare soil to reflect soil conservation practices that assure ground cover on steep slopes.

Table 5-19. Relative tendencies for conversion from cropland, Ecological Watershed scenario.

| | | Land Use | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | - | - | - | - | - |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 1 | 2 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 1 | 4 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 0 | 1 | 1 | 1 | 2 |
| 7 | Distance to streams > 400 m | 2 | 2 | 2 | 2 | 1 |
| 8 | Distance to house ≤ 400 m | 1 | 1 | 1 | 1 | 2 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | - | - | - | - | - |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | 2 | 2 | 2 | 2 | 1 |

Assumptions: Part of the cropland is close to the streams where irrigation water supply is easiest. Cropland is assumed fertile and high productive. Cropland is therefore most likely to remain cropland, particularly true close to streams and houses. Cropland close to stream cannot change towards bare soil as proper soil conservation practices avoid such change. Cropping in the upper part of the watershed is slightly discouraged to avoid over-exploitation of this region, so cropland is less likely to remain cropland here.

Table 5-20. Relative tendencies for conversion from bare soil, Business as Usual scenario.

| | | ------------------ Land Use ------------------ | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 0 | 1 | 1 | 1 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 2 | 1 | 1 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 4 | 1 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 1 | 3 | 2 | 0 | 1 |
| 7 | Distance to streams > 400 m | 1 | 1 | 1 | 0 | 1 |
| 8 | Distance to house ≤ 400 m | 1 | 2 | 1 | 0 | 2 |
| 9 | Distance to house > 400 m | 4 | 1 | 1 | 1 | 1 |
| 10 | Slope ≤ 10 degrees | 2 | 1 | 1 | 1 | 1 |
| 11 | Slope > 10 degrees | 6 | 1 | 1 | 1 | 0 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A land unit with bare soil is more likely to remain fallow if many adjacent land units have a bare soil as well. Isolated land unit with bare soil always changes toward another land use. It is based on the assumption that land improvements are more likely to be made at single land unit rather than larger uncultivated areas. Fallow land close to houses or streams is more likely to change towards cropland or pasture rather than scrub or forest. Bare soil on steep slopes never changes towards cropland. Bare soil does not change towards forest because of lack of any incentives for deforestation and conservation under this scenario.

Table 5-21. Relative tendencies for conversion from pasture, Business as Usual scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | - | - | - | - | - |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 3 | 1 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 6 | 1 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 2 | 1 | 1 | 1 |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | - | - | - | - | - |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 2 | 2 | 2 | 1 | 1 |
| 11 | Slope > 10 degrees | 2 | 1 | 1 | 0 | 0 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A land unit with pasture is more likely to remain pasture if many adjacent land units are pasture as well. This promotes clustering. Pasture close to roads has the greatest chance to remain pasture. In general, pasture has a small chance to change towards cropland or forest. Pasture on steep slopes never changes towards cropland or forest.

Table 5-22. Relative tendencies for conversion from scrub, Business as Usual scenario.

| | | ----------------- Land Use ----------------- | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | - | - | - | - | - |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 2 | 1 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 4 | 1 | 1 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | 1 | 2 | 0 | 1 | 1 |
| 6 | Distance to streams ≤ 400 m | 2 | 2 | 4 | 1 | 1 |
| 7 | Distance to streams > 400 m | 2 | 2 | 2 | 0 | 1 |
| 8 | Distance to house ≤ 400 m | - | - | - | - | - |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | - | - | - | - | - |
| 11 | Slope > 10 degrees | 3 | 1 | 1 | 1 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A scrub land unit is more likely to remain scrub if many adjacent land units have scrub as well. Scrub at greater distance from roads will change to something else, and most likely into pasture or cropping land. Conversion from scrub towards cropland occurs relatively little. Scrub close to streams is more likely to remain scrub, whereas scrub far from streams cannot change into forest. Scrub at steeper slopes is more likely to erode and change towards bare soil.

Table 5-23. Relative tendencies for conversion from forest, Business as Usual scenario.

| | | ------------------ Land Use ------------------ | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 1 | 0 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 2 | 1 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 3 | 1 |
| 4 | Distance to roads ≤ 500 m | 1 | 1 | 1 | 1 | 3 |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 1 | 1 | 1 | 1 | 2 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 1 | 1 | 1 | 4 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 0 | 1 | 1 | 1 | 3 |
| 11 | Slope > 10 degrees | 1 | 1 | 1 | 2 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | - | - | - | - | - |

Assumptions: A forest land unit is more likely to remain forest if many adjacent land units are forest as well. Forest close to roads and close to houses is most likely to be cut and be converted into cropland. This conversion is most likely in relatively flatter areas. Forest on steep hill slopes will most likely remain forest. Forest on relatively flat land does not change towards bare soil.

Table 5-24. Relative tendencies for conversion from crops, Business as Usual scenario.

| | | Land Use | | | | |
|---|---|---|---|---|---|---|
| | Conversion rule | Bare S. | Pasture | Scrub | Forest | Crops |
| 1 | 0 , 1 or 2 adjacent land units same LUC | 1 | 1 | 1 | 0 | 1 |
| 2 | 3, 4 or 5 adjacent land units same LUC | 1 | 1 | 1 | 1 | 2 |
| 3 | 6, 7 or 8 adjacent land units same LUC | 1 | 1 | 1 | 1 | 3 |
| 4 | Distance to roads ≤ 500 m | - | - | - | - | - |
| 5 | Distance to roads > 500 m | - | - | - | - | - |
| 6 | Distance to streams ≤ 400 m | 1 | 1 | 1 | 1 | 2 |
| 7 | Distance to streams > 400 m | - | - | - | - | - |
| 8 | Distance to house ≤ 400 m | 1 | 1 | 1 | 1 | 3 |
| 9 | Distance to house > 400 m | - | - | - | - | - |
| 10 | Slope ≤ 10 degrees | 3 | 1 | 1 | 1 | 1 |
| 11 | Slope > 10 degrees | 5 | 1 | 1 | 1 | 1 |
| 12 | Elevation < 1525 m | - | - | - | - | - |
| 13 | Elevation 1525 - 1725 m | - | - | - | - | - |
| 14 | Elevation > 1725 m | 2 | 2 | 2 | 2 | 1 |

Assumptions: Cropland is distributed in a scattered manner, with less clustering occurring than under the Corporate farming and Ecological Watershed scenarios. Cropland is most likely to remain cropland close to houses and streams. Furthermore, cropland has a high chance to change towards bare soil because many farmers abandon fields after the soil has been depleted or because fields eroded and become unusable. This occurs particularly on the steeper hill slopes. Most cropping takes place in the lower and middle parts of the watershed.

## Results and Discussion

### Land Use Patterns in 2025

Figure 5-2 shows the initial 1989 land use (LU) pattern and the those simulated for 2025. Table 5-25 gives the percentages covered by each LU type, and Table 5-26 indicates the area of each LU type per person. All four land use patterns are considerably different. This was expected because the relative tendencies were different for the scenarios.

Table 5-25. Percentages covered per land use type for four different land use patterns.

| | | --------------- Simulated for the year 2025 --------------- | | |
|---|---|---|---|---|
| LUC type | Initial data (1989 data) | Corporate Farming | Ecological Watershed | Business as Usual |
| Bare soil | 12.1 | 12.0 | 4.2 | 20.5 |
| Pasture | 38.3 | 31.5 | 36.6 | 37.1 |
| Scrub | 24.6 | 18.2 | 15.6 | 18.1 |
| Forest | 16.0 | 12.0 | 30.0 | 5.7 |
| Crops | 9.0 | 26.3 | 13.6 | 18.6 |

The *Corporate Farming* land use pattern is characterized by a 192% increase in the total area of cropland (+130% per capita) in 36 years. Pasture remains the most dominant land use type although its area decreased with 18% (-36% per capita). It is assumed that cropland and pasture are used very intensively for production of crop and dairy products. Only part of the production is assumed necessary for self-consumption. The remainder is transported and marketed outside the watershed.

The most significant changes in the *Ecological Watershed* land use pattern were the 65% decrease in the area bare soil (-76% per capita) and the 88% increase in the area of forest (+28% per capita). This reflects the importance of land conservation in this scenario. The 51% increase in cropland in 35 years was of the same magnitude as the assumed population growth during the same period. Cropland is used to grow crops for family consumption and some cash crops.

Land conservation was not important in the *Business as Usual* scenario. During the 35 year period, the area in forest decreased 64% (-78% per capita) and the area of bare soil increased 69% (+6% per capita). Over 20% of the land in the watershed is without vegetation as a result of excessive soil erosion, numerous landslides and abandonment of fields. The per capita area of cropland increased with 30%. This increase is assumed necessary to compensate for the decreased productive capacity of the soil and the lower per hectare production levels. Per capita food production in 2025 is assumed not higher than in 1989.

Table 5-26. Per capita area (ha) for each land use type for four different land use patterns.

| | | -------------- Simulated for the year 2025 --------------- | | |
|---|---|---|---|---|
| LUC type | Initial data (1989 data) | Corporate Farming | Ecological Watershed | Business as Usual |
| Bare soil | 0.170 | 0.130 | 0.040 | 0.180 |
| Pasture | 0.538 | 0.344 | 0.350 | 0.327 |
| Scrub | 0.346 | 0.199 | 0.149 | 0.160 |
| Forest | 0.225 | 0.130 | 0.287 | 0.050 |
| Crops | 0.126 | 0.287 | 0.130 | 0.164 |
| TOTAL | 1.405 | 1.091 | 0.956 | 0.881 |

Note: data are computed based on a population of the 7,525 ha administrative Cabuyal region of 5,357 (initial data), 6,900 (Corporate Farming), 7,870 (Ecological) and 8,545 (Business as Usual) persons. Table 6-1 explains the population growth under each scenario.

The simulated change in the percentages covered by each land use type during a 100 year period is show in Figures 5-3 (Corporate farming), Figure 5-4 (Ecological Watershed) and Figure 5-5 (Business as Usual). The dotted black line at the year 2025 in these figures indicates the land use distribution as given in Table 5-26 and Figure 5-3b,c,d. The areas of each land use type still changes significantly after 100 years for the *Corporate Farming* scenario. On the other hand, a fairly stable land use distribution was reached at the end of the simulated period for the *Ecological Watershed* and *Business as Usual* scenarios. Small fluctuations still occurred, caused by the stochastic nature of the model. The near-equilibrium only applies to the total areas covered by each land use type. The actual allocation of a (nearly) constant area of a particular LU type over the land units that comprise the watershed may still slightly change from year to year.

The aim of the model was to generate a land use pattern for 36 years in the future, not necessarily at a near-equilibrium distribution of land use. Whether an equilibrium land use distribution is actually reached within the 36 simulated years, depends on the selection of the relative tendencies for LU change and the choice of parameter YRLUC. It would be difficult to *a priori* calculate a set of appropriate input values for which the land use distribution approaches a specific equilibrium because (i) the total number of relative tendencies is large and (ii) each land unit may have a different set of applicable conversion rules. Moreover, there is no ground to assume that the distribution of land use in the Cabuyal River watershed will indeed approach equilibrium near 2025, or at any other point in the future.

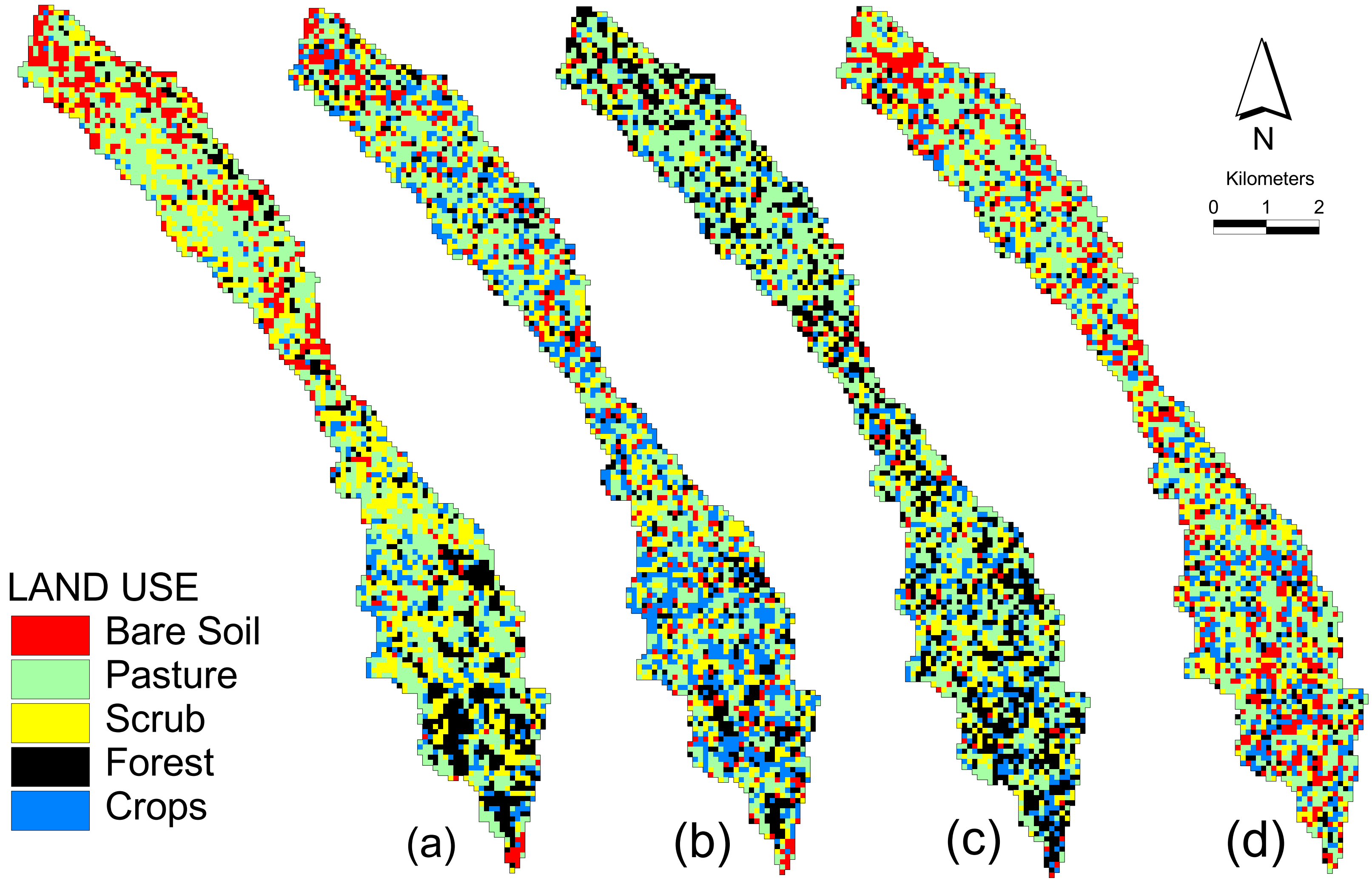



Figure 5-2. Distribution of land use in the Cabuyal River watershed. a) Actual situation in 1989. b) simulated 2025 Corporate Farming scenario; c) simulated 2025 Ecological Watershed scenario; d) simulated 2025 Business as Usual scenario.

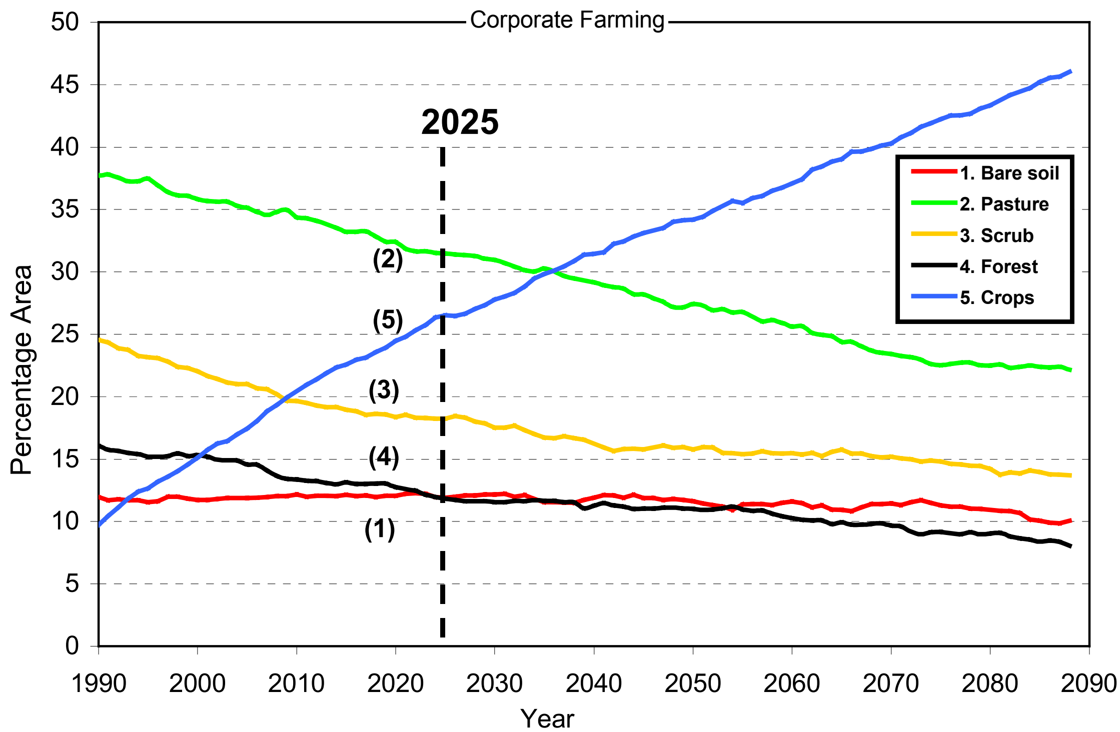



Figure 5-3. Simulated changes in land use distribution for the Corporate Farming scenario.

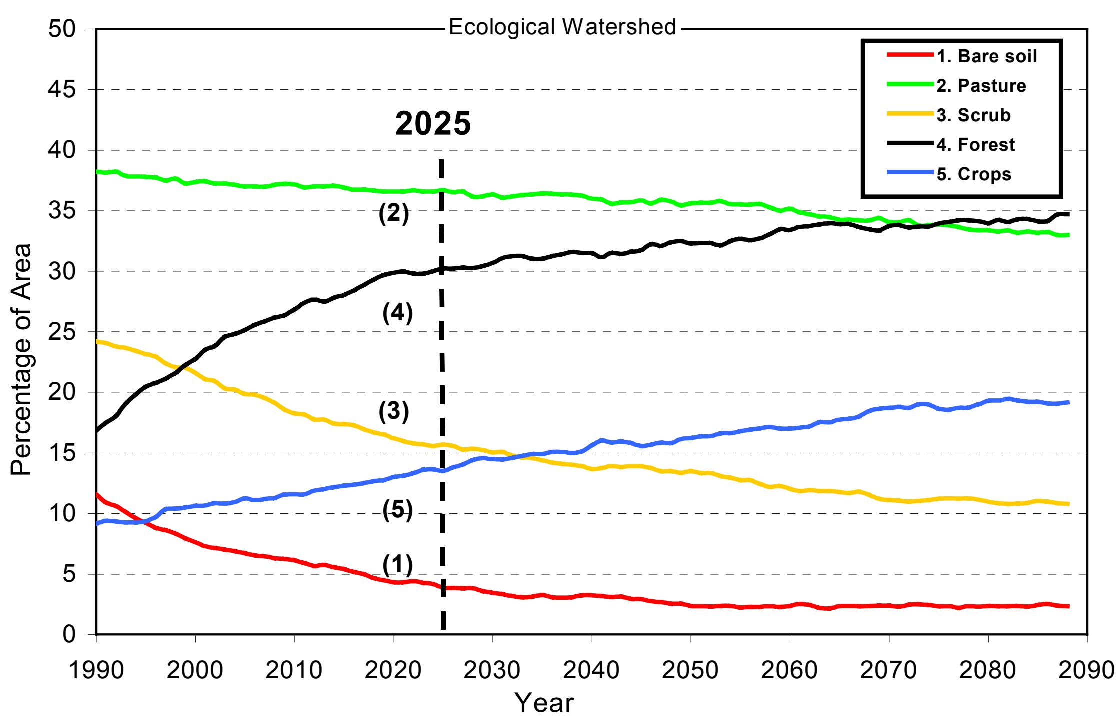



Figure 5-4. Simulated changes in land use distribution for the Ecological Watershed scenario.

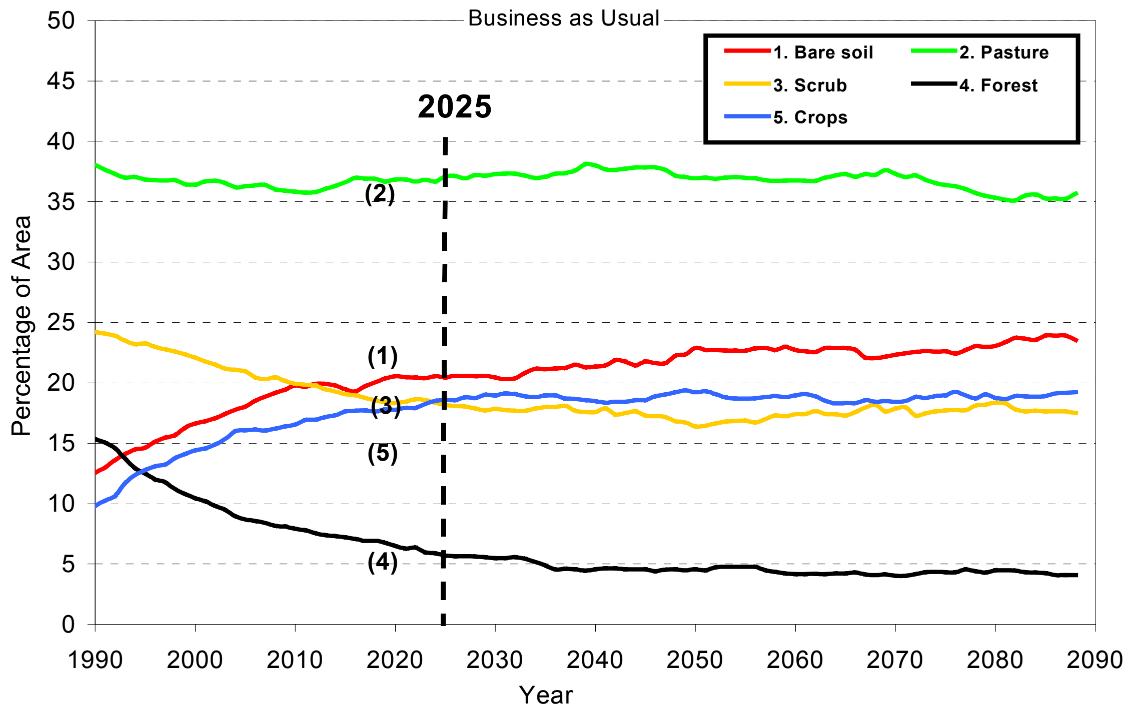



Figure 5-5. Simulated changes in land use distribution for the Business as Usual scenario.

Sensitivity Analysis

Sensitivity to random number generator SEED.

Table 5-27 shows the mean and standard deviation of land use after 100 years, based on 100 replicates with different random number SEED. Standard deviations never exceed 1%. The LU type with the smallest mean also has the smallest standard deviation, and the LU type with the largest mean has the largest standard deviation. These results illustrate that simulation results will differ with different SEED, although the direction of LU changes under any scenario remains predictable and is distinctly different from the other scenarios.

Note that the percentages covered by each LU type in Table 5-25 are close, but not identical to the mean percentages in Table 5-27. The data in Table 5-25 are associated with only one particular simulation run for each scenario, whereas the data in Table 5-27 are the averaged results of 100 simulation runs for each scenario.

Table 5-27. Mean and standard deviation of the percentage area covered by each land use type, after 36 simulated years (1990-2025), based on 100 replicates of each simulation run. Each replicate used a different random number generator seed.

| LU type | Corporate Farming | | Ecological Watershed | | Business as Usual | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. | Mean | Std.Dev |
| Bare soil | 11.99 | 0.60 | 3.99 | 0.38 | 19.52 | 0.66 |
| Pasture | 30.33 | 0.84 | 37.07 | 0.79 | 35.45 | 0.96 |
| Scrub | 16.84 | 0.75 | 15.26 | 0.73 | 19.13 | 0.73 |
| Forest | 12.53 | 0.65 | 30.17 | 0.71 | 6.70 | 0.47 |
| Crops | 28.30 | 0.76 | 13.50 | 0.55 | 19.20 | 0.66 |

Sensitivity to relative tendencies.

The results of a 50% increase in the relative tendency towards all five LU types are shown in Table 5-28. For the case of 36 simulated years, the 50% higher tendency for bare soil caused a 28.7% increase in the area of bare soil (relative to the reference data, not the initial situation). The 50% higher relative tendencies towards any of the other four LU types resulted in 23.4% more pasture, 33.3% more scrub, 26.1% more forest and 23.2% more crops, respectively. Over the entire 100-year period, these changes were 41.3% more bare soil, 43.4% more pasture, 60.3% more scrub, 32.7% more forest and 40.0% more crops, respectively. The standard deviations did not significantly change.

Sensitivity to parameter YRLUC

Figure 5-6 shows the change in percentage covered by the 5 land use types for 3 different values of YRLUC: 0.05 (slowest changing), 0.10 and 0.15 (fast changing). The results explain two important aspects of the model behavior.

First, a higher value of YRLUC resulted in faster changes. This was best visible for forest, bare soil and crops. However, the "near equilibrium" states that the LU type reached after many simulated years were not affected by the value of YRLUC. Thus, the direction of land use change was affected only by the definition of the scenario in terms of relative tendencies of LU change, not by the speed with which these LU changes occurred.

Secondly, apart from the difference in speed with which LU change occurred, the three curves associated with a particular LU type did not show the same pattern of change. The curves sometimes cross and move in opposite directions during specific periods in time. Choosing the same SEED did not have any affect because the different value of YRLUC causes LU changes to occur at different land units and at different years. A change in one or more relative tendencies would have the same affect. Thus, there is advantage to specifying the same seed value if either YRLUC and/or relative tendencies changed.

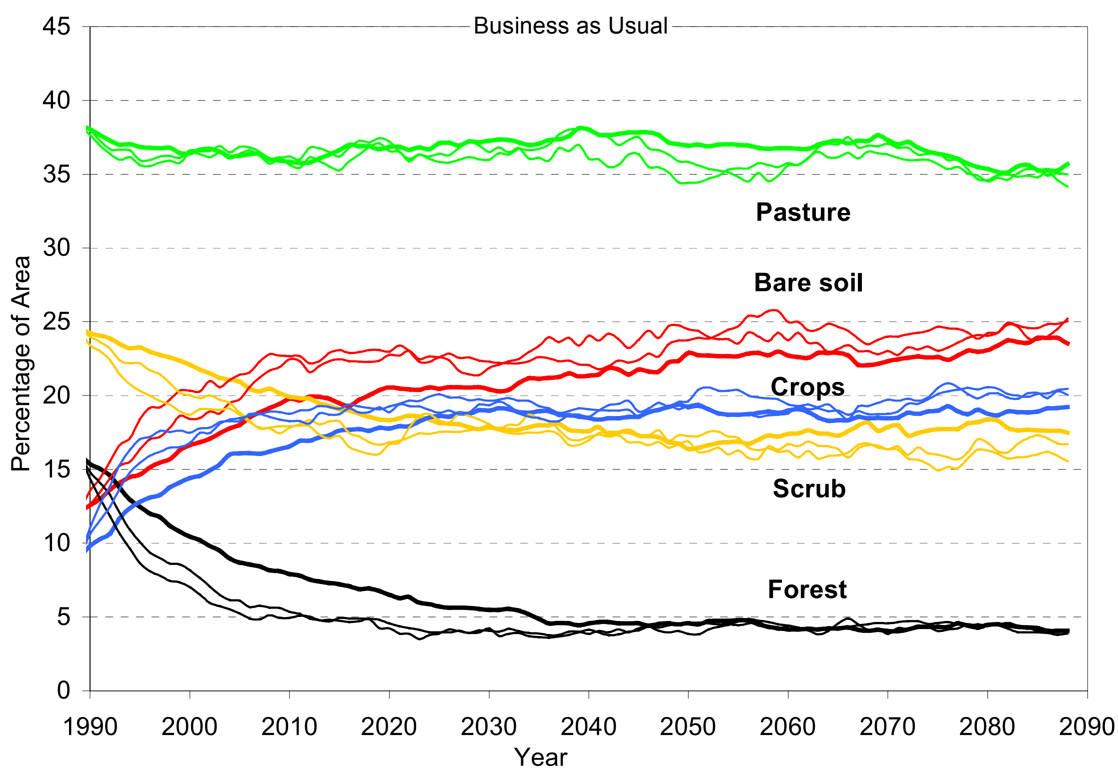



Figure 5-6. Simulated changes in the percentage of the area covered by each land use type, for the Business as Usual scenario, using YRLUC values of 0.05 (thicker, slowest changing curves), 0.10 (middle curves), and 0.15 (fastest changing curves), using the same random number generator SEED.

Table 5-28. Mean and standard deviation of the percentage area covered by each land use type, after 36 simulated years (1990-2025) and 100 simulated years (1990-2089), based on 100 replicates of each simulation run.

| | BARE SOIL | | PASTURE | | SCRUB | | FOREST | | CROPS | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | St.Dev. | Mean | St. Dev. | Mean | St. Dev. | Mean | St.Dev. | Mean | St. Dev. |
| 1989, INITIAL SITUATION | 12.1 | n/a | 38.3 | n/a | 24.6 | n/a | 16.0 | n/a | 9.0 | n/a |
| SIMULATED, AFTER 36 YEARS | | | | | | | | | | |
| Reference data | 19.5 | 0.7 | 35.5 | 1.0 | 19.1 | 0.7 | 6.7 | 0.5 | 19.2 | 0.6 |
| 50% higher R.T. bare soil[1] | 25.1 | 1.1 | 33.3 | 1.0 | 17.7 | 0.7 | 6.4 | 0.4 | 17.5 | 0.7 |
| 50% higher R.T. pasture | 16.9 | 0.6 | 43.6 | 0.8 | 16.2 | 0.6 | 6.2 | 0.4 | 17.1 | 0.7 |
| 50% higher R.T. scrub | 18.3 | 0.6 | 31.8 | 0.8 | 25.7 | 0.6 | 6.4 | 0.4 | 17.9 | 0.7 |
| 50% higher R.T. forest | 19.0 | 0.7 | 34.1 | 0.9 | 18.5 | 0.8 | 8.4 | 0.5 | 20.0 | 0.7 |
| 50% higher R.T. crops | 18.5 | 0.8 | 33.5 | 0.9 | 17.9 | 0.7 | 6.5 | 0.5 | 23.6 | 0.7 |
| SIMULUATED, AFTER 100 YEARS | | | | | | | | | | |
| Reference data | 23.4 | 0.9 | 35.5 | 1.0 | 17.0 | 0.6 | 4.5 | 0.4 | 19.6 | 0.7 |
| 50% higher R.T. bare soil | 33.1 | 1.1 | 31.6 | 1.0 | 14.8 | 0.6 | 3.9 | 0.3 | 16.6 | 0.7 |
| 50% higher R.T. pasture | 17.1 | 0.8 | 50.9 | 1.1 | 13.0 | 0.7 | 3.8 | 0.3 | 15.3 | 0.7 |
| 50% higher R.T. scrub | 21.4 | 0.9 | 29.4 | 1.0 | 27.2 | 0.9 | 4.2 | 0.3 | 17.7 | 0.6 |
| 50% higher R.T. forest | 23.0 | 0.9 | 32.9 | 1.0 | 16.2 | 0.7 | 6.0 | 0.4 | 21.8 | 0.7 |
| 50% higher R.T. crops | 22.0 | 1.0 | 31.0 | 0.9 | 15.5 | 0.7 | 4.1 | 0.3 | 27.4 | 0.8 |

[1] R.T. = relative tendency for change towards a particular land use type.

## Conclusions

The land use change model was developed to create three plausible land use grids that were needed to simulate three scenarios with SWBM. These land use grids were created based on very few data. The core of the land use change model were the sets of *a priori* specified relative tendencies of land use change. These relative tendencies were based on subjective interpretation of how land use changes might occur with respect to six spatially variable landscape characteristics. In order to reduce the level of complexity and define three understandable sets of relative tendencies, the number of land use classes was reduced from 10 to 5.

The relative tendencies were constant over time. For any set of relative tendencies, this resulted in a land use distribution that reached a near equilibrium after many years of simulation. The desired land use distribution—in terms of percentages covered by each land use type, not the exact allocation of land use types to the land units— was thus *a priori* determined for each scenario. Temporal changes in the actual biophysical and socioeconomic land use drivers and in the magnitudes of their effects were not considered. Moreover, effects of land use drivers were only considered indirectly, namely by using them to define the rules that related landscape characteristics to relative tendencies of land use change. These model features may limit the applicability of the model for other purposes. The model is quite different from other land use change models that can simulate, or at least account in some way, for dynamics in land use drivers. The land use pattern is then a true, and *a priori* unknown outcome of the interaction between drivers and landscape.

The land use change model was adequate for the purpose of this study. The distribution of land use in the three plausible land use patterns for the *Corporate Farming*, *Ecological Watershed,* and *Business as Usual* scenarios were quite different, representing different directions of future development. The hydrologic behavior of the watershed and annual (stream) water yields is expected to be different for each land use pattern too.

Because the model is stochastic, different seed-values for the random number generator always resulted in slightly different land use distributions, but the standard deviation of the percentage area covered by any land use type was always less than 1%. The definition of the scenario—in terms of relative tendencies—determined the direction of land use change and the near-equilibrium distribution of land use. Theoretically, the relative tendencies could have a minor affect on the speed of LU changes at the beginning of the simulation (when the near-equilibrium distribution of land use has not been reached yet), but this was not noticeable in this case. The annual probability of LU change (YRLUC) was the only factor that determined the speed of land use changes. This model parameter had only a minor (and random) affect on the near-equilibrium distribution of land use.

# CHAPTER 6
# IMPLICATIONS OF VARIOUS PATHS OF DEVELOPMENT ON WATER AVAILABIITY IN THE CABUYAL RIVER WATERSHED

## Introduction

Inhabitants of the Cabuyal River watershed in southwest Colombia are increasingly concerned about the state and management of water resources in their watershed. They have experienced less predictable river flows and increasing water shortages during the dry seasons during the last decade. Local stakeholders attributed this to the combined effects of continuous deforestation, absence of adequate soil conservation techniques, and overuse of water in the upper part of the watershed (de Fraiture et al., 1997, Ravnborg and Ashby, 1996). Conflicts arose between communities about these water shortages and the impact of excessive water extraction on water availability in downstream communities. Water extraction from streams has always been virtually unregulated, potentially allowing farmers and industries to extract large amounts of water. These practices could reduce water availability in downstream communities to levels below the water demand. Simulation results of the potential water supply indicated that (i) flow rates vary over time and space, (ii) changes in land use/land cover changes significantly affect the hydrology of the watershed and flow rates (Chapter 3) and (iii) a considerable fraction of the available water is used, particularly for irrigation in the dry season (Chapter 4).

Farmers, community leaders, regional land planners and policy makers are among those who make decisions about the use of land and water resources in the watershed. Experience with decision-making processes in the watershed showed that is increasingly important to provide quantitative information about the state of water resources, and how demand and supply of water resources could change over space and time as a result of changes in land use, population growth and demographic shifts within the watershed, industrial development, and construction of dams. Decision-makers are less interested in receiving optimal recommendations to questions than in having a presentation of a series of realistic alternative options that aid in outlining an optimal, preferred path for future development (Bouma, 1997). One way to provide such information is through scenario analysis.

Scenarios are not predictions of the future but technical surveys based on a number of different philosophies about the future. Scenarios provide a framework for assessing strategic policy and management options for future development. They aim at describing the state of a region and its resources as a result of hypothetical, though still well-founded and plausible changes in socio-economic, biophysical, and/or institutional conditions. It is unlikely that a region will end up exactly as any of the scenarios. However, scenarios could characterize part of the whole and help navigate an acceptable, intermediate path of future development.

Scenario analysis have successfully been applied at different spatial scales, ranging from the field and farm levels, via regional and watershed levels, to the continental and global levels (e.g. Netherlands Scientific Council for Government Policy, 1992; Fresco et al., 1994). At a watershed scale, scenario analysis can help improve the integrated management of a multitude of watershed resources such as cropland, pastures, forests and water, to each of which a multitude of often conflicting interests may relate (Knapp et al., 1999). Specifically, scenario analysis can help:

- indicate the degree of water scarcity and suggest biophysical and socio-economic boundary conditions for sustainable agricultural production and use of resources,
- understand under what future conditions and conflicts about water resource use can be expected, who will be affected, where in the watershed and during what time of the year,
- catalyze discussions among stakeholders and a multi-institutional forum for analysis and negotiation about resource use, and gain commitment of stakeholders to solutions, and
- stimulate strategic thinking and build consensus on strategic and policy issues, and help decision-makers identify the best options for future development.

The objective of this chapter is to analyze the implications of various paths of development on water availability in the Cabuyal River watershed. Three different scenarios were defined based on contrasting but plausible views of the future of the watershed in 2025. Each scenario is characterized by a different magnitude and direction of land use change, different size and spatial distribution of the population, and increased water demand. The scenarios were used to assess water scarcity in the watershed under different situations. Water scarcity was quantified by determining the reduction in stream flow due to water use, water availability throughout the watershed, the percentage of river flow that was used, whether critical water shortages occurred, during what time of the year and at what locations.

## Materials and Methods

### Scenario Descriptions

Three scenarios for the Cabuyal River watershed were developed. They describe quite contrasting but plausible futures for watershed in the year 2025. A detailed description of the economy, demography and landscape that characterizes the watershed under each scenario is given in Appendix F. These descriptions were based on expert knowledge on possible directions of development in the watershed (E.B. Knapp, 1999, personal communication). They served as the basis for creation of the data sets needed to simulate the scenarios.

The *Corporate Farming* 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 product dominate the activities in the watershed. Land and water resources are intensively used. In the *Ecological Watershed* scenario, it is assumed that regional authorities and local communities have a strong mandate to conserve forest and water resources, regulate stream flows and avoid destructive agricultural practices. This mandate is shaped by a worldwide effort to reduce environmental degradation, as well as by the contribution of the Cabuyal River to a hydropower plant. The economy and land use under the *Business as Usual* scenario are closest to the situation it has been 25 years in the past. Small-scale subsistence farming and processing of cassava and coffee on farmers remain the main activities. However, the population and distribution of land use did change. Most forest has disappeared due to slash and burn activities, and much land has eroded or is left with a bare soil. This reflects the lack of incentives for land conservation.

Demographics

CIAT carried out a household census in the Cabuyal River watershed in 1995 (E.B. Knapp, 1999, personal communication). Every house was georeferenced and all inhabitants were counted. It was assumed that each family occupied one house. A total of 910 families with 5,357 people lived in the administrative Cabuyal region (7,526 ha). About 70% of the houses were located within 150 m of the roads (Figure 4-5). The population density varied from more than 200 people km$^{-2}$ in the communities of Pescador and Crucero in the middle of the watershed to below 25 people km$^{-2}$ in Buena Vista and El Oriente in the upper part of the watershed (Table 4-2).

It was assumed that the population in the watershed increases in each scenario, but with growth rates ranging from the United Nations (1998) low to the high projections for Colombia (see Appendix G). Demographic data for 1995 and the three scenarios are given in Table 6-1. The population size was necessary to quantify domestic water use and calculate the area land per capita (which will be shown later).

Although SWBM does not require data on the distribution of the population and the specific locations of houses, providing this information is part of the characterization of the watershed. An actual map of houses enhances the understanding of the landscape, indicates the domestic water demand in different parts of the watershed, and will help identify specific areas in which the potential for water allocation problems and water shortages are highest.

Figure 6-1 shows a map with hypothetical locations of the houses for each scenario. The number of houses (dots) in each map is equal to the number of families in Table 6-1, assuming a one-to-one relationship between families and houses. The future locations of the houses were determined by manually changing the original 1995 house data set (Figure 4-5), an ArcView shapefile. No model was used to determine the location of houses.

Table 6-1. Demographic data in 1995 and estimates for the three scenarios in 2025, for the 7,526 ha administrative Cabuyal region.

| Scenario | Persons | Families | Growth 1995-2025 | Spatial distribution of houses |
|---|---|---|---|---|
| 1) Actual, 1995 [1] | 5,357 | 910 | N/A | Scattered throughout watershed; highest density near roads. |
| 2) Corporate Farming | 6,900 | 1,250 | 29%; below the low UN projection | 50% of people live in the middle of the watershed near the highway. |
| 3) Ecological Watershed | 7,870 | 1,340 | 47.1%; medium UN projection | 90% of the people live in 8 major groups, called *conjuntos.* |
| 4) Business as Usual | 8,545 | 1,450 | 59.5%, high UN projection | Highly scattered throughout the watershed, also far from roads. |

[1] Based on a census by CIAT (E.B. Knapp, personal communication, 1999).

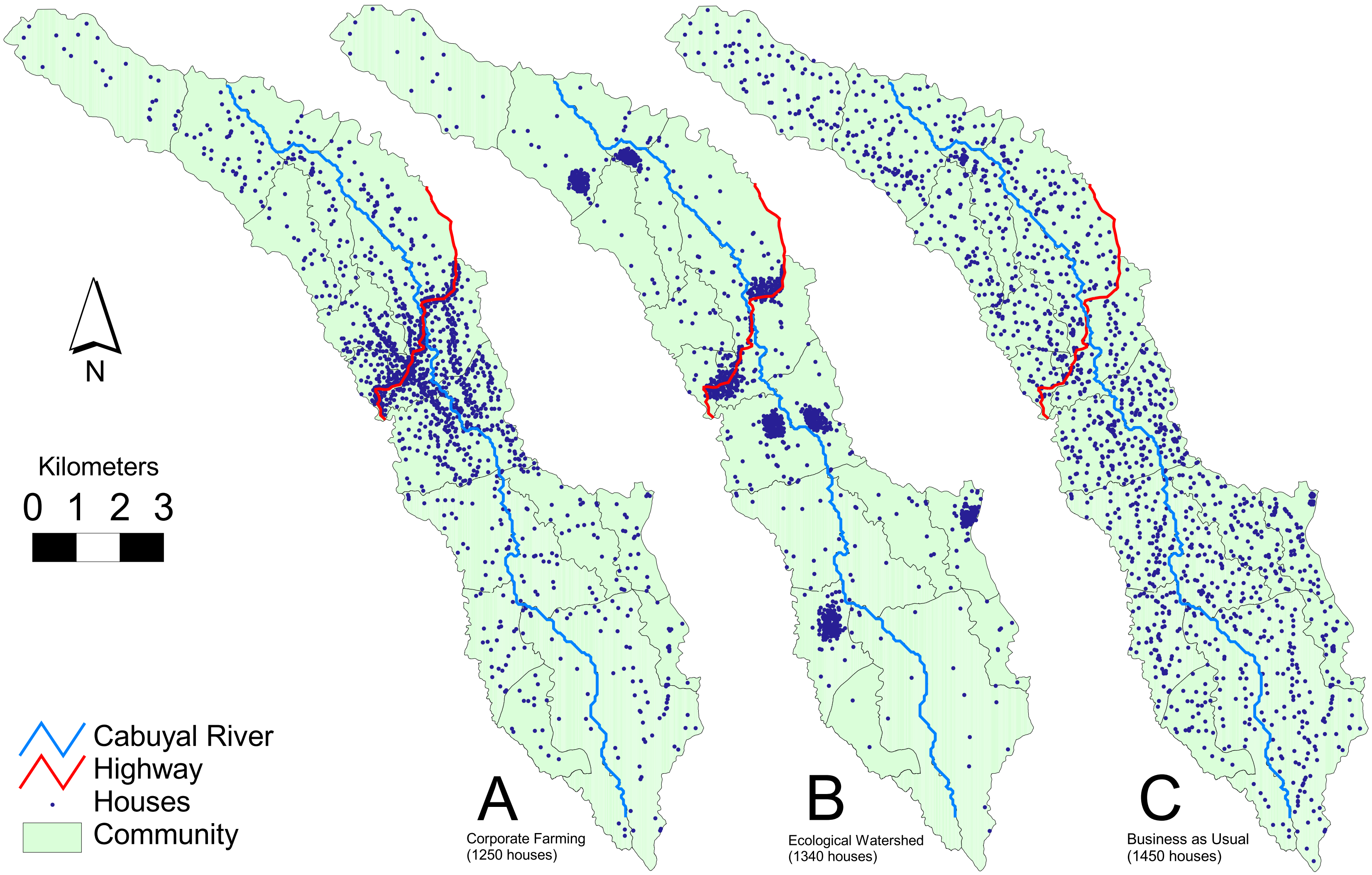



Figure 6-1 Hypothetical location of houses in 2025 in the administrative Cabuyal region; (A) Corporate Farming; (B) Ecological Watershed; (C) Business as Usual scenario.

Land use pattern

The land use pattern is one of the most important characteristics of the landscape that distinguishes each of the three scenarios. Another model was developed to generate land use patterns for any number of years in the future (Chapter 5). Changes in the land use were made stochastically on a land unit basis in each year. The direction of land use change was based on relative tendencies to move from one to another land use type, accounting for six characteristics of the landscape that were considered relevant in describing land use changes: (1) Euclidean distance to roads, (2) distance to streams, (3) distance to houses, (4) terrain slope, (5) elevation, and (6) land use type of adjacent land units. A different LUC pattern was created for each scenario for the year 2025 (Figure 5-2). The distribution of land use, and the per capita area per land use type, is given in Table 6-2 for each scenario.

Table 6-2. Area covered (%) and the area per person[1] (ha, between parentheses), per land use type, in 1989 and for the land use patterns of the three scenarios.

| | | ------------- Simulated for the year 2025 ------------- | | |
|---|---|---|---|---|
| LUC type | 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) |

[1] Based on the population data in Table 6-1.

Use of Watershed Model

The Spatial Water Budget Model (SWBM) was used to simulate each scenario. SWBM is a continuous simulation, distributed parameter, watershed scale model that simulates water supply and demand over space and time on a daily basis using GIS data structures. The SWBM model was explained in detail in Chapters 2 and 4. The model is not a tool to solely simulate hydrological processes and to perform water supply/demand analyses for any location in the stream network at any time of the year. Instead, the model was designed as a tool to assess water scarcity before and after applying external stresses. These external stresses were population growth, land use changes, and increased domestic, industrial and agricultural water use. Water scarcity in the watershed was evaluated by looking at the reduction in stream flows and water availability throughout the watershed, the percentage of river flow that was extracted throughout the year, whether critical water shortages occurred, during what time of the year, and at what locations in the watershed.

Simulations were done using the weather data collected at the Jose Domingo farm in the Cabuyal River watershed from January 1, 1994 through December 31, 1997 (see Chapter 2). These four years will be referred to as years 1, 2, 3 and 4 during the discussion of simulation results to avoid thinking that the years 1994-1997 that are actually simulated—instead, the year 2025 is simulated for each scenario, with 4 replicates of that year.

## Quantification of Water Use

As differences in the amount of water use are greatest between different months rather than between different days within the same month, average water use was assumed the same on all days within the same month. However, water use was specified per day in the SWBM model as the model works on a daily basis. Water use may actually vary throughout the day, depending on the hours of operation of industries, when cooking and bathing takes place, and when fields are irrigated. The SWBM model cannot account for this variation. It was assumed that households, industries and farms have small water tanks that provide sufficient buffer capacity to meet higher than average water demand during certain hours of the day.

<u>Corporate farming scenario</u>

Figure 6-2 shows the amounts of water used for the Corporate Farming scenario. It was assumed that water use per person increased from 120 L/d in the 1990s (Ramirez, 1992) to 150 L/d. The total rate of water use by 6,900 inhabitants was thus 1,035 $m^3d^{-1}$ (12.0 L/s). It was also assumed that the three drinking water systems that take water from the Cabuyal River (Table 4-3) were redesigned, that all households in the administrative Cabuyal region had access to them, and that the these systems supplied water at a rate of 1,728 $m^3d^{-1}$ (20 L/s) all year. This is the actual rate of water extraction from the river at three locations in the upper part of the watershed (Figure 6-7a). The largest drinking water system accounted for 75% of the drinking water supply, whereas the other two systems supplied 12.5% each.

Any unused drinking water was assumed to leave the drinking water systems in the lowest lying community of El Caimito (Figure 4-4). This is beyond the end point of the Cabuyal River, thus outside the catchment of the Cabuyal River. Any surplus drinking water was therefore not returned to the river and considered as used within the watershed.

Industries were located near the Pan-American Highway in the middle of the watershed. They operated all year around and used 2,600 $m^3d^{-1}$ (30.1 L/s), which is 25 times more than in the mid 1990s (de Fraiture et al., 1997). Water was taken in equal amounts from the river at two locations close to the industries (Figure 6-7a).

Irrigation water use was based on simulated long-term average irrigation water demands for a tomato crop (Table 4-7). Irrigation was applied to 300 ha cropland and 300 ha pasture. The specific land units to which irrigation was applied were randomly selected from the land units classified as, respectively, *Crops* and *Pasture* (300 from each class) in Figure

5-2. The average rate of irrigation was 2.0 mm $d^{-1}$ during August and September and 1.5 mm $d^{-1}$ during June, July and October. This application rate is sufficient to meet average irrigation requirements for a tomato crop in the region (Table 4-7). An irrigation efficiency of 0.75 was assumed. During all other months, 50 ha cropland was irrigated at 1.5 mm $d^{-1}$. Irrigation water was extracted at equal rates from six dams that were specifically constructed to store irrigation water. The rate of water extraction per dam was thus 2,000 $m^3d^{-1}$ in August and September, 1,500 $m^3d^{-1}$ in June, July and October, and 125 $m^3d^{-1}$ in all other months (10 $m^3d^{-1}$ water is needed to irrigate 1 ha at a rate of 1 mm $d^{-1}$).

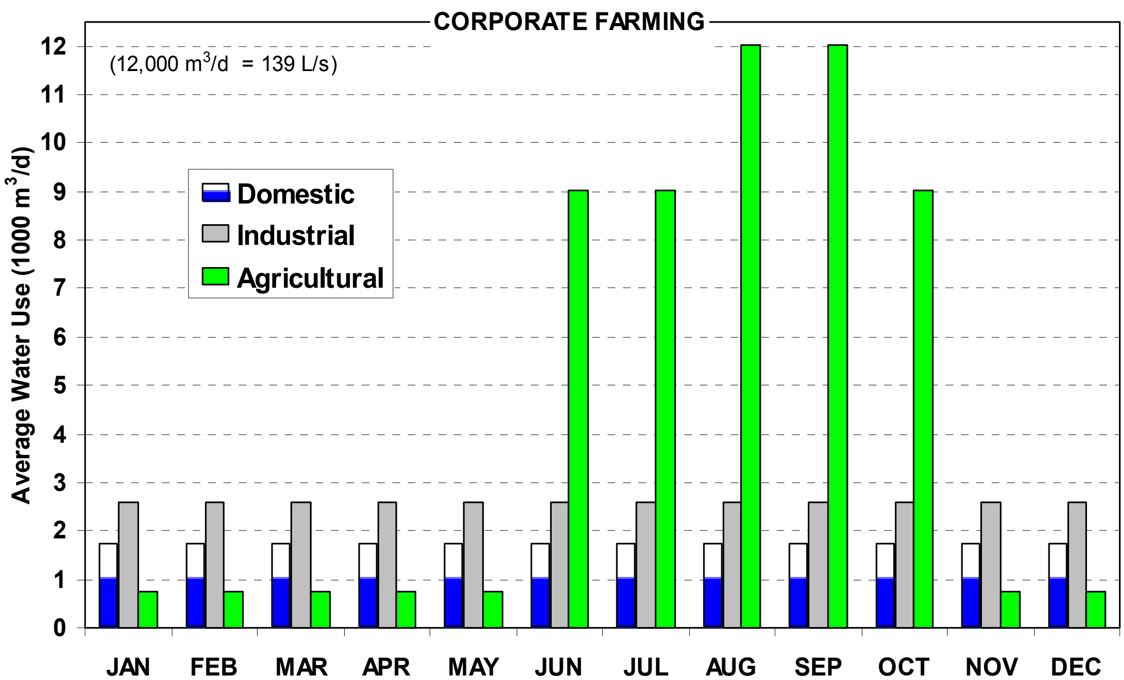



Figure 6-2. Average daily water use for the Corporate Farming scenario, per month. The white part of the "domestic" bar indicates unused water of the drinking water systems.

Ecological watershed scenario

Figure 6-3 shows the amounts of water used for the Ecological Watershed scenario. The construction and capacity of the drinking water system was assumed the same as in the Corporate Farming scenario, supplying water at a rate of 1,728 $m^3d^{-1}$ (20 L/s). Per capita water use was assumed 150 L/d, resulting in a total domestic water use of 1,181 $m^3d^{-1}$ (13.7 L/s) by all 7,870 inhabitants. The few agricultural processing industries operated all year around and used water at a rate 432 $m^3d^{-1}$ (5 L/s), which is 4 times more than in the mid 1990s (de Fraiture et al., 1997). Water for industrial use was extracted from the river at a single location (Figure 6-7b).

Irrigation water needs were based on the irrigation of 200 ha cropland at an average rate of 2.0 mm $d^{-1}$ during July, August, and September (total 4,000 $m^3d^{-1}$) and at an average rate of 1.5 mm $d^{-1}$ during June and October (total 3,000 $m^3d^{-1}$). The irrigation efficiency was 0.75. Irrigation water was extracted at equal rates at 12 locations in the river (Figure 6-7b).

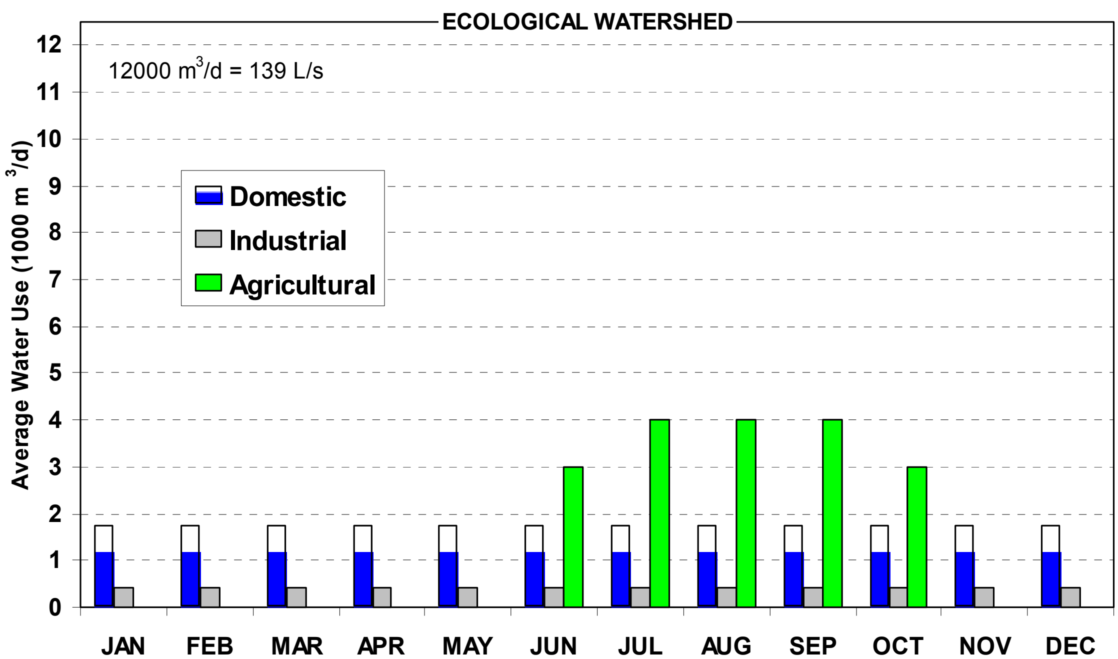



Figure 6-3. Average daily water use for the Ecological Watershed scenario, per month. The white part of the "domestic" bar indicates unused water of the drinking water systems.

<u>Business as usual scenario</u>

Figure 6-4 shows the amounts of water used for the Business as Usual scenario. Water use by the 8,545 inhabitants was assumed 150 L/d per capita, resulting in a total domestic water use of 1,282 $m^3d^{-1}$ (14.8 L/s). The construction and capacity of the drinking water system was assumed to the same as in the other scenarios, supplying water at a rate of 1,728 $m^3d^{-1}$ (20 L/s). No major industrial activity took place. The only industries were household-based and used on average 259 $m^3d^{-1}$ (3 L/s) water, which is 2.5 times more than in the mid 1990s. This water was taken from the drinking water system rather than from the river.

Each of the 1,450 families had a 0.1 ha vegetable yard which was irrigated at a rate of 3 mm $d^{-1}$ from July through September (total 4,350 $m^3d^{-1}$) and at 2 mm $d^{-1}$ in June and October (total 2,900 $m^3d^{-1}$). These rates were higher than in the other scenarios to reflect a lower irrigation efficiency of 0.50. No irrigation was applied from October through May. Irrigation water was extracted at equal rates from 15 different locations (Figure 6-7c).

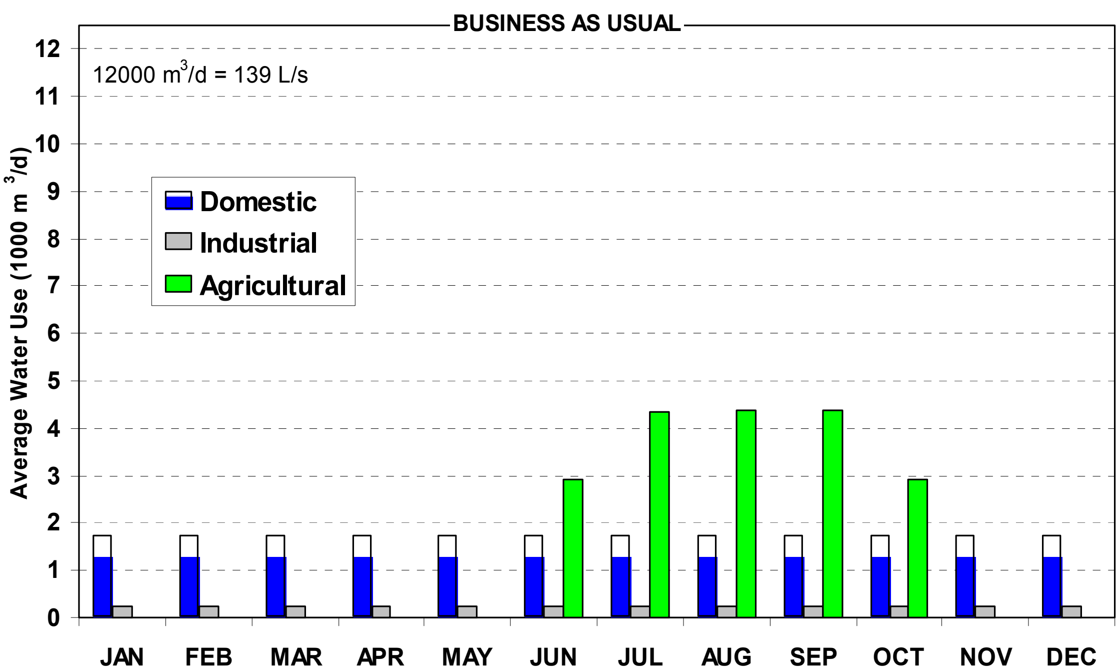



Figure 6-4. Average daily water use for the Business as Usual scenario, per month. The white part of the "domestic" bar indicates unused water of the drinking water systems.

Operation of Dams

Corporate farming scenario

Six dams were located in the watershed. Five of them were located on the Cabuyal River and the sixth dam was located on a tributary stream in the upper part of the watershed (Fig. 6-7a), at the place where a small lake (*laguna)* was in the 1990s. The purposes of the dams were to store irrigation and to maintain minimum flow rates. It was assumed that irrigation water could be taken only from these dams, not from any other locations in the river. Two different ways of construction and operation of these dams were analyzed.

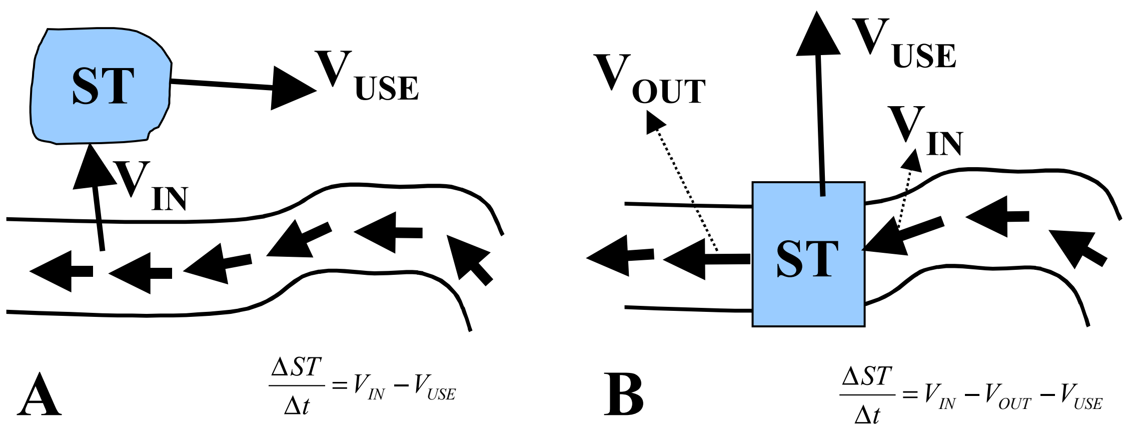



Figure 6-5. Construction of dams from where irrigation water is taken; (A) dams are built as external reservoirs connected to the stream; (B) dams are actually constructed in the river.

Irrigation dam case 1. Figure 6-5a shows a situation where the dams are reservoirs connected to the stream via a pipe. Water could only be pumped from the stream towards each reservoir at a rate $V_{IN}$, which was set to 850 $m^3d^{-1}$ (9.84 L/s) all year (unless the stream flow was insufficient to sustain this rate), until the maximum storage $ST_{MAX}$ of 150,000 $m^3$ (each reservoir) was reached. These dams could not be used to control river flows.

Water extraction from dams for irrigation purposes ($V_{USE}$) was a separate process. Equal amounts of water were extracted from the six dams at any day. From water use from each dam,$V_{USE}$, was 2,000 $m^3d^{-1}$ in August and September, 1,500 $m^3d^{-1}$ in June, July and October, and 125 $m^3d^{-1}$ in all other months. The initial storage of each dam at January 1 was 75,000 $m^3$, half the dam capacity.

Irrigation dam case 2. Dams in this case were built in the river (Fig. 6-5b) for storing water for irrigation purposes as well as for controlling minimum flows during the dry season. Because of this double functionality, the storage capacity of each dam was increased to 300,000 $m^3$. Initial storage in each dam was set to the dam capacity. Each dam was kept at full storage capacity all year, unless minimum flow requirements did not allow this.

The minimum required flow rate was set at 400 L/s at the watershed outlet. Minimum flow rates at each dam were chosen proportionally to the average ratio of the simulated flow rate at each dam over the flow rate at the watershed outlet (Figure 6-6). The fractions that were graphically determined in Figure 6-6 were multiplied with 400 L/s, resulting in minimum flow rates at the six dams of 385, 310, 256, 229, 148 and 42 L/s, respectively. Slight adjustments were made in these fractions to account for the differences in magnitude of flows and any water extraction along the flow path.

The curve in Figure 6-6 is similar to the 50% percentile curve in Figure 3-15 for flow lengths smaller than 16.5 km. They were not exactly identical as simulations were carried out using different land use data. For flow lengths greater than 16.5 km, the curves are different because they correspond to different sections of the stream network. The most southern dam in Figure 6-6 was not located in the Cabuyal River but in one of its tributary streams.

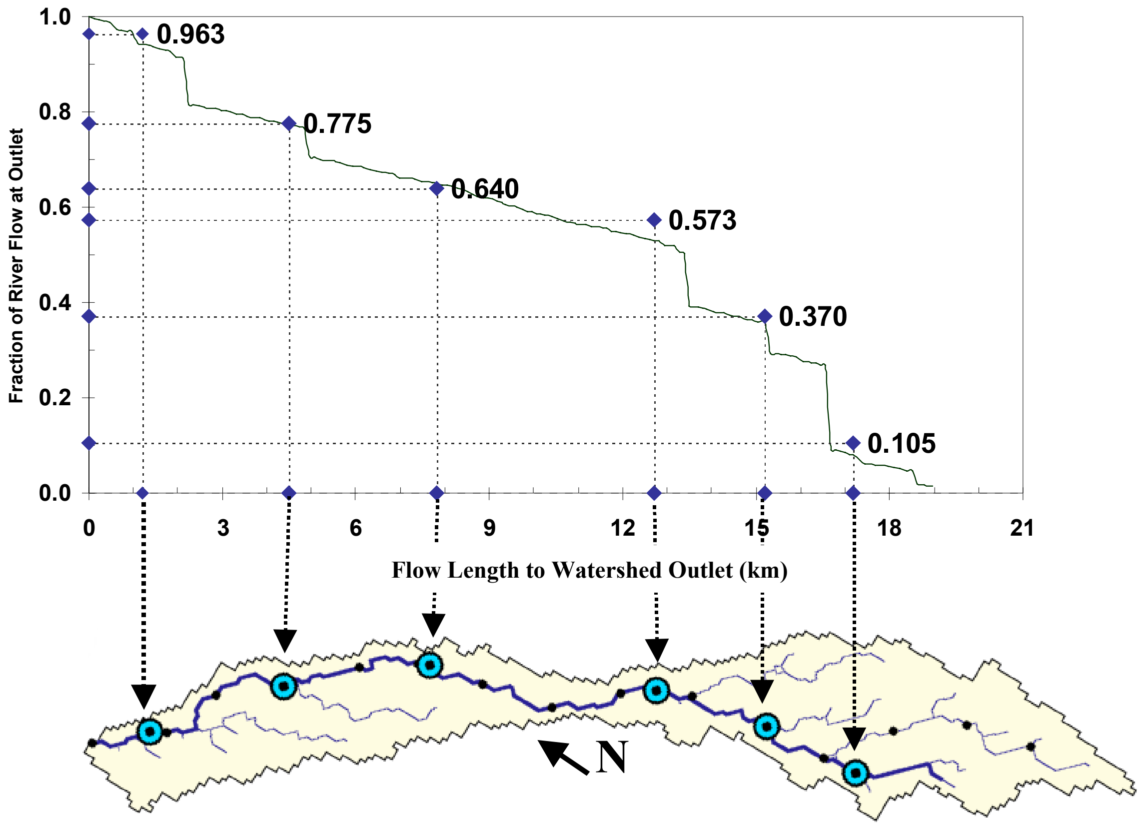



Figure 6-6. Graphical derivation of the long-term average ratio of simulated river flow near each of the six dams to river flow at the watershed outlet.

<u>Ecological farming scenario</u>

Under the Ecological Watershed scenario, a total of 15 smaller dams with a capacity of 100,000 $m^3$ each were built in the river. They were used to reduce peak flow rates to 1,500 L/s and to sustain a minimum flow rate of 350 L/s during the dry season at the watershed outlet. The dams were not used to store irrigation water. By controlling river flow rates gradually throughout the watershed, these dames were assumed to provide fertile plots and wetlands along the entire river. Twelve dams were located in the Cabuyal River at equal distances between 1.5 and 18 km (flow length) from watershed outlet, and three dams in the three largest secondary streams (Figure 6-7c).

The operation of dams was modeled by specifying three parameters: (1) the dam's equilibrium fraction $FR_{ST,x,d}$, which controls the rate of water flow out of a dam, (2) the minimum required flow rate at the dam, $V_{MIN,x,d}$, and (3) the maximum allowed flow rate at the dam, $V_{MAX,x,d}$. The equilibrium fraction $FR_{ST,x,d}$ was set to 0.5 for each dam, maintaining an equilibrium water storage of 50,000 $m^3$ in each dam. The minimum required flow rate and the maximum allowed flow rate at each dam were determined proportionally to the average ratio of the simulated flow rate at each dam over the flow rate at the watershed outlet (Figure 6-6). Table 6-3 gives the minimum and maximum flow rates at each dam. All parameters were constant all year.

Table 6-3. Distance to watershed outlet and minimum required and maximum allowed flow rates at the fifteen dams in the Ecological Farming scenario.

| Distance to outlet[1] (km) | Minimum flow, $V_{MIN,x}$ (L/s) | Maximum flow, $V_{MAX,x}$ (L/s) | Distance to outlet (km) | Minimum flow, $V_{MIN,x}$ (L/s) | Maximum flow, $V_{MAX,x}$ (L/s) |
|---|---|---|---|---|---|
| 0.0 | 350 | 1500 | 12.0 | 192 | 824 |
| 1.5 | 340 | 1459 | 13.5 | 138 | 592 |
| 3.0 | 283 | 1214 | 15.0 | 127 | 544 |
| 4.5 | 272 | 1167 | 16.5 | 95 | 407 |
| 6.0 | 241 | 1034 | 18.0 | 54 | 232 |
| 7.5 | 229 | 984 | 2.2 | 35 | 149 |
| 9.0 | 218 | 932 | 13.8 | 34 | 146 |
| 10.5 | 202 | 867 | 16.8 | 32 | 137 |

[1] No dam was located at the outlet itself (0.0 km distance). The dams at 2.2, 13.8 and 16.8 km from the outlet were located in the secondary streams, all other dams in the Cabuyal River.

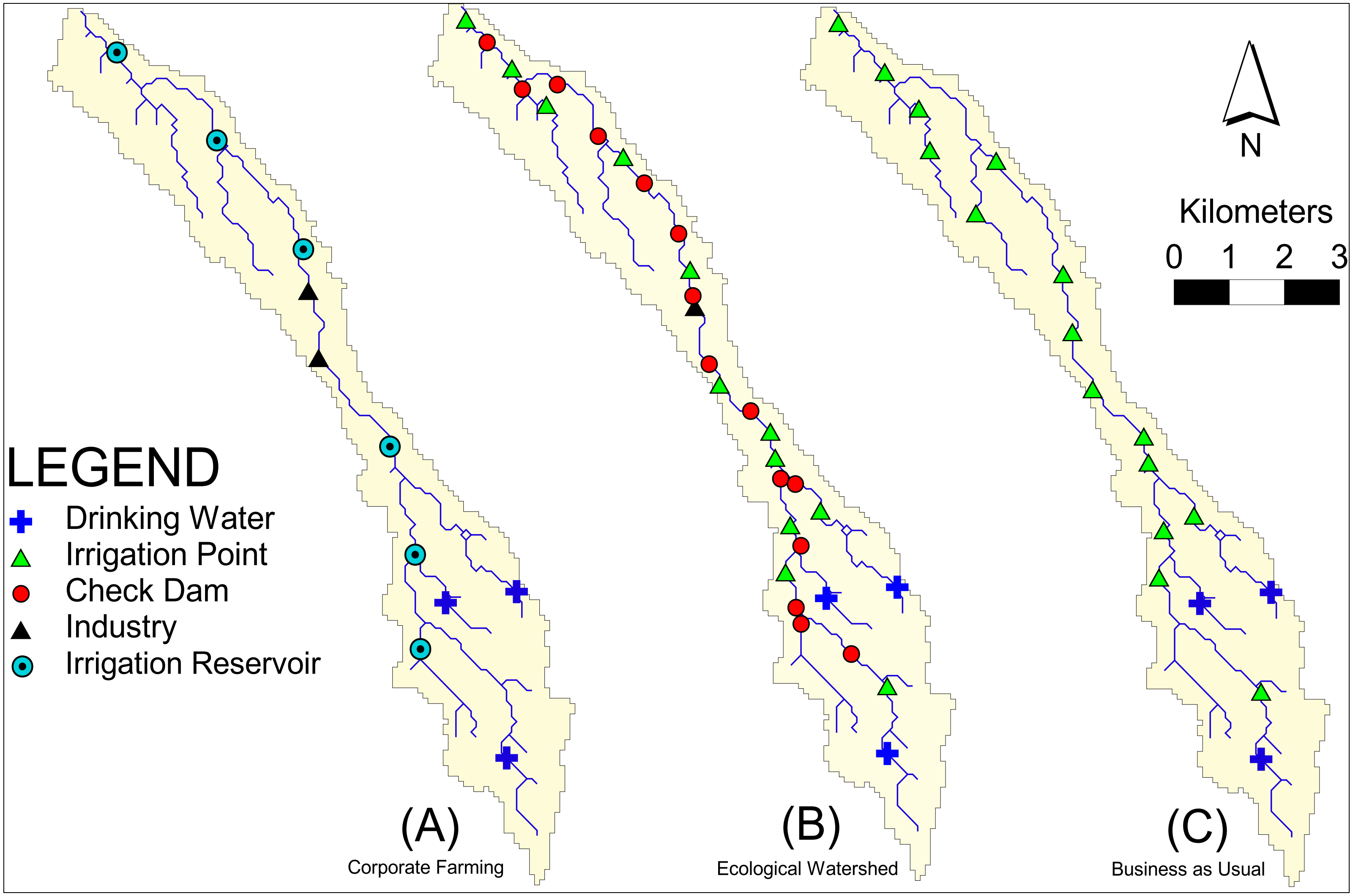



Figure 6-7. Locations where water is extracted in the Cabuyal River watershed for domestic use, industrial use and agricultural use; (A) Corporate Farming scenario; (B) Ecological Watershed scenario; (C) Business as Usual scenario.

## Results and Discussion

Table 6-4 gives a summary of the water balance and simulated base flow and river flows, before water use and dams. These data characterize the hydrological response of the watershed. The difference between the 1989 situation and the three scenarios are caused by difference in land use. In the Ecological Watershed scenario, average annual ET was high because of the relatively large area of pasture and forest. Consequently, average river flow was lowest for this scenario. Surface runoff was also low because the pasture and forest vegetation provided good ground cover, which reduced surface runoff. The Business as Usual scenario showed opposite effects. Average annual surface runoff and river flow were highest among all scenarios, which was caused by the large area of bare soil and smallest evaporative capacity of the land cover. Simulated flows for the Corporate Farming scenario were in between those for the two other scenarios. Table 6-5 gives a summary of the water supply/ demand balance for 1989 and the three scenarios in 2025. Simulation results for each scenario are discussed in detail.

Table 6-4. Simulated water flows and components of the water balance, before accounting for water use and impedance by dams, in 1989 and the three scenarios in 2025. Data are averaged over 4 simulated years.

| Scenario | Mean ET (mm/yr) | Average BFI[1] (-) | Minimum baseflow | Average baseflow | Average runoff | Minimum river flow | Average river flow |
|---|---|---|---|---|---|---|---|
| | | | L/s | | | | |
| Initial, 1989 [2] | 917 | 0.813 | 238 | 670 | 154 | 249 | 824 |
| Corporate Farming | 865 | 0.808 | 246 | 706 | 168 | 259 | 874 |
| Ecological Watershed | 945 | 0.856 | 219 | 681 | 115 | 228 | 796 |
| Business as Usual | 813 | 0.779 | 269 | 721 | 205 | 283 | 926 |

[1] BFI = Base Flow Index, the ratio of base flow to river flow. The remaining fraction of the river flow, 1-BFI, indicates the contribution of surface runoff to river flow.
[2] Data from Table 3-13.

Table 6-5. Summary of the average annual water supply/demand balance in 1989 and the three scenarios in 2025.

| Water class | Initial, 1989 [a] | | Corporate Farming (external basins) | | Corporate Farming (dams built in river) | | Ecological Watershed (dams built in river) | | Business as Usual | |
|---|---|---|---|---|---|---|---|---|---|---|
| Situation | Min [b] | Max [c] | Min | Max | Min | Max | Min | Max | Min | Max |
| | ---- Volume of Water, $m^3 d^{-1}$ ---- | | | | | | | | | |
| Domestic water use | 329 | 329 | 1,035 | 1,035 | 1,035 | 1,035 | 1,181 | 1,181 | 1,282 | 1,282 |
| Surplus drinking water | 1,399 | 1,399 | 693 | 693 | 693 | 693 | 547 | 547 | 187 | 187 |
| Industrial water use | 102 | 102 | 2,600 | 2,600 | 2,600 | 2,600 | 432 | 432 | 259 [d] | 259 [d] |
| Irrigation water use | 0 | 1,503 | 750 | 12,000 | 750 | 12,000 | 0 | 4,000 | 0 | 4,350 |
| Intake external basins | N/A | N/A | 750 [f] | 5,100 | N/A | N/A | N/A | N/A | N/A | N/A |
| Change dams in river | N/A | N/A | N/A | N/A | 0 | -28,510 [i] | 0 | -15,578 [i] | N/A | N/A |
| Net water extraction [g] | 1,728 | 3,231 | 5,078 [j] | 9,428 [j] | 5,078 | 16,328 | 2,160 | 6,160 | 1,728 | 6,078 |
| River flow before use [e] | 240,000 [k] | 21,514 | 240,000 | 23,105 | 240,000 | 22,378 | 240,000 | 20,822 | 240,000 | 27,734 |
| River flow after use [e] | 238,272 | 18,181 | 234,922 | 13,677 | 234,922 | 34,560 | 237,840 | 30,240 | 238,272 | 21,656 |
| % Extracted [h] | 0.7 % | 15.5 % | 2.1 % | 40.8% | 2.1 % | 32.1 % | 0.9 % | 16.9 % | 0.7 % | 21.9 % |

[a] Based on the simulation results presented in Chapters 3 and 4.
[b] Data in the "Min" columns are those for the day with lowest water use and a high water supply, resulting in the lowest % extracted.
[c] Data in the "Max" columns are those for the day with highest water use and a low water supply, resulting in the highest % extracted.
[d] Water for industrial use taken from the drinking water system. Surplus intake by the drinking water system is reduced accordingly.
[e] "Use" includes actual water use (domestic, industrial and agricultural) and the effect of dam operation on stream flow.
[f] Equal to lowest level of irrigation water use, which is needed to maintain dam at full capacity.
[g] Water extraction from river. If there are dams, actual water use may be different depending on changes in the storage in the dams.
[h] Calculated as (net water extraction) / (river flow before use - change dams in river).
[i] The negative value indicates water release from dams to meet minimum flow requirements after water extraction.
[j] Does not include irrigation water use because this is taken from the external basins rather than from the river.
[k] The values of "River flow before use" listed in the "Min" columns have been set at 240,000 (2,778 L/s) in all four situations.

Corporate Farming Scenario

Case 1: reservoirs external to the river.

Figure 6-8 shows the simulated river flow at the watershed outlet, as well as the change in river flow due to water extraction. The difference between both curves indicates the amount of river flow before water use was accounted for (gross supply).

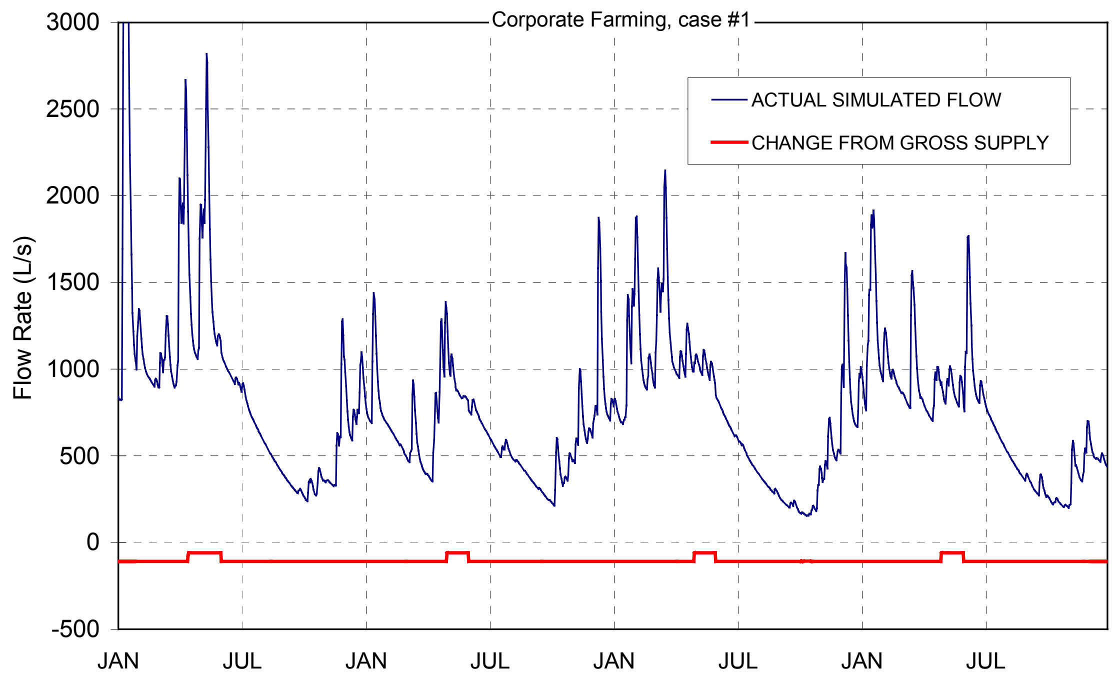



Figure 6-8. Simulated river flow and change from gross river flow due to water use, for the Corporate Farming scenario with dams as external reservoirs, for 4 years.

There were only two different levels of water extraction. Water extraction from the river was minimal when all reservoirs were at full storage capacity and irrigation water use was minimal. This occurred only during a relatively short time of the year, namely in May, and can be recognized as the periods during which the bottom line in Figure 6-8 is slightly higher (less water extraction). Total water use was then 5,078 $m^3d^{-1}$ (58.8 L/s) (1,728 $m^3d^{-1}$ domestic, 2,600 $m^3d^{-1}$ industrial and 750 $m^3d^{-1}$ recharge of reservoirs). Water use was maximal at the remaining part of the year, when all reservoirs were below storage capacity and sufficient water was available is the river to refill all reservoirs at the maximum rate of 850 $m^3d^{-1}$. Water use then amounted 9,428 $m^3d^{-1}$ (109.1 L/s) (1,728 $m^3d^{-1}$ domestic, 2,600 $m^3d^{-1}$ industrial, 5,100 $m^3d^{-1}$ recharge of dams).

Figure 6-9 shows the percentage of river flow that was actually extracted for domestic, industrial and agricultural uses. It was as low as 2.1% during a wet period in the first year, but reached 40.8 % in the dry summer of the third year (see also Table 6-5).

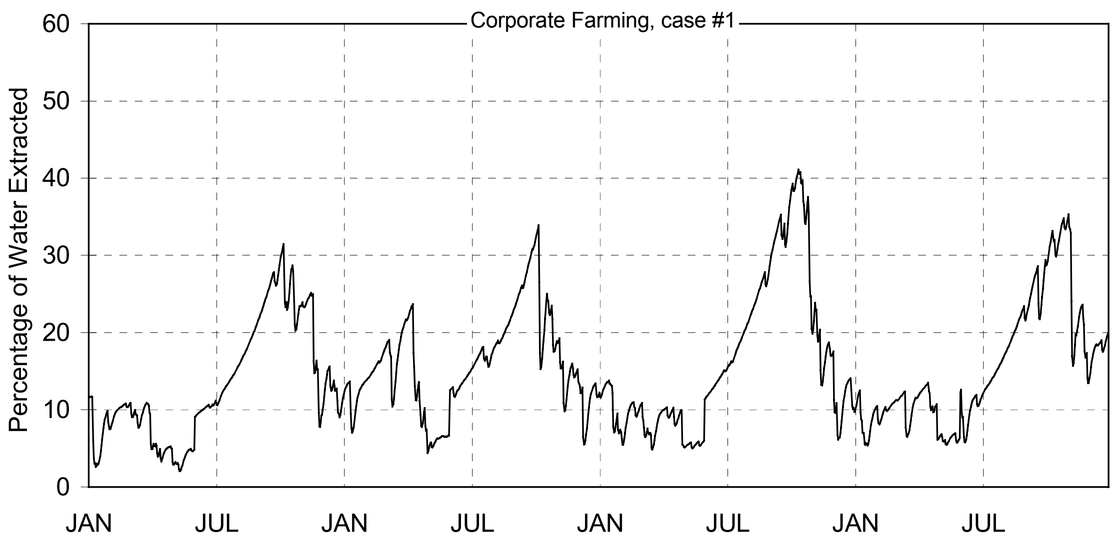



Figure 6-9. Simulated percentage of river flow that was extracted for direct use or refilling of reservoirs, for the Corporate Farming scenario with dams as external reservoirs, for 4 years.

Figure 6-10 shows the reduction in river flow at different distances from the watershed outlet due to water extraction. The discontinuities—representing a further decrease in the river flow—occurred at water extraction locations or where smaller streams merged with the Cabuyal River (reductions in stream flow are additive).

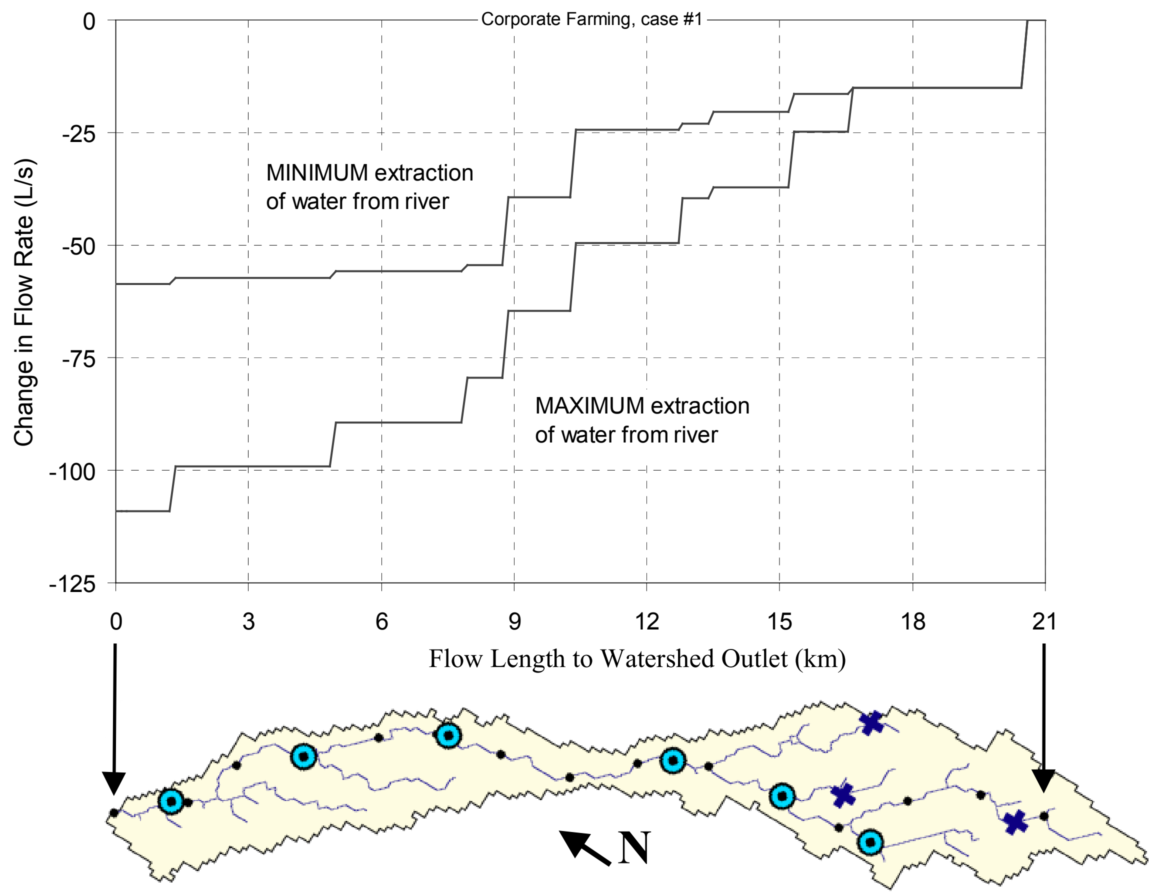



Figure 6-10. Simulated change in river flow due to water extraction, as function of flow length to the watershed outlet, for the Corporate Farming scenario with dams as external reservoirs, for a day with minimal and a day with maximal water extraction. The flow length between the small black dots is 1.5 km.

Figure 6-11 shows the volume of water stored in each reservoir over a period of 4 years. This curve was identical for all reservoirs and in each year, which was a consequence of the identical operational settings and water use from the reservoirs. River flow appeared sufficient at every day and at every reservoir to sustain the rate of 850 $m^3d^{-1}$ at which every reservoir was filled (except for the short periods around May, when the dams were full). About 13% of the capacity of each reservoir (19,500 out of 150,000 $m^3$) was not used. This surplus capacity would allow increasing irrigation water use, or the storage volume of the reservoirs could be decreased.

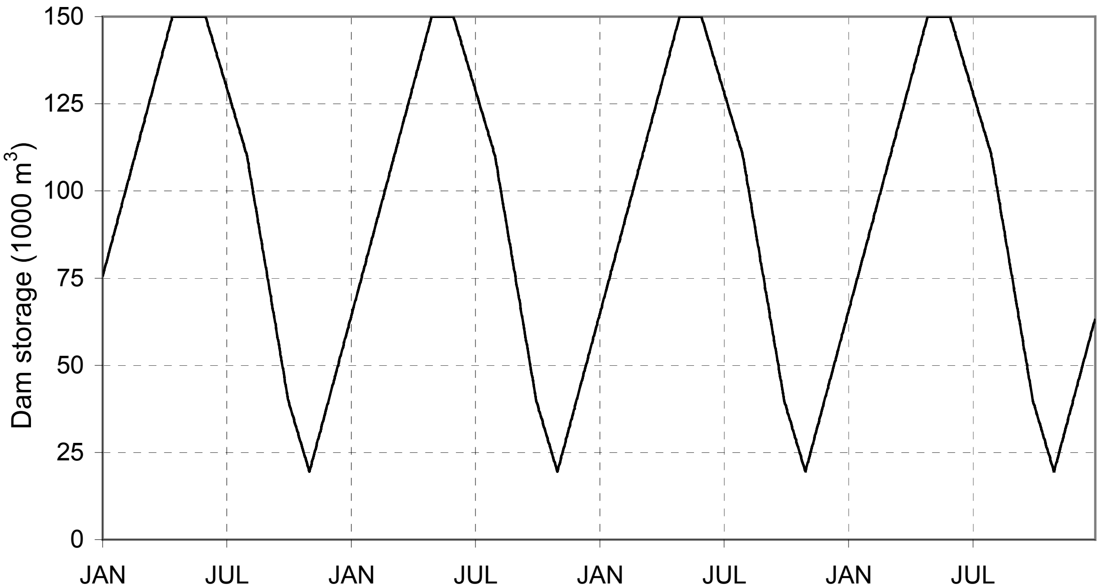



Figure 6-11. Simulated volume of water stored in each dam during a period of 4 years, for the Corporate Farming scenario with dams as external reservoirs.

Case 2: dams built in river

Figure 6-12 shows the simulated flow rate at the watershed outlet after considering water use and impedance by dams. The dams in the river sustained a minimum flow of 400 L/s during the dry season. Simulated river flow did not immediately increase above 400 L/s because the first rains after the dry season were used to refill dams until they reaches storage capacity again. This refilling process corresponds to the strong reductions in flow rates.

The percentage of river flow that is extracted over the 4 years is given in Figure 6-13. It was as low as 2.1% during the wet season, whereas as much as 32.1% of available water was used at the end of the dry season (Table 6-5). If there had been no dams, the latter value would have been 61.0%. Thus, dams not only helped to sustain minimum flow rates, but also reduced the maximum percentage of water used during the dry season.

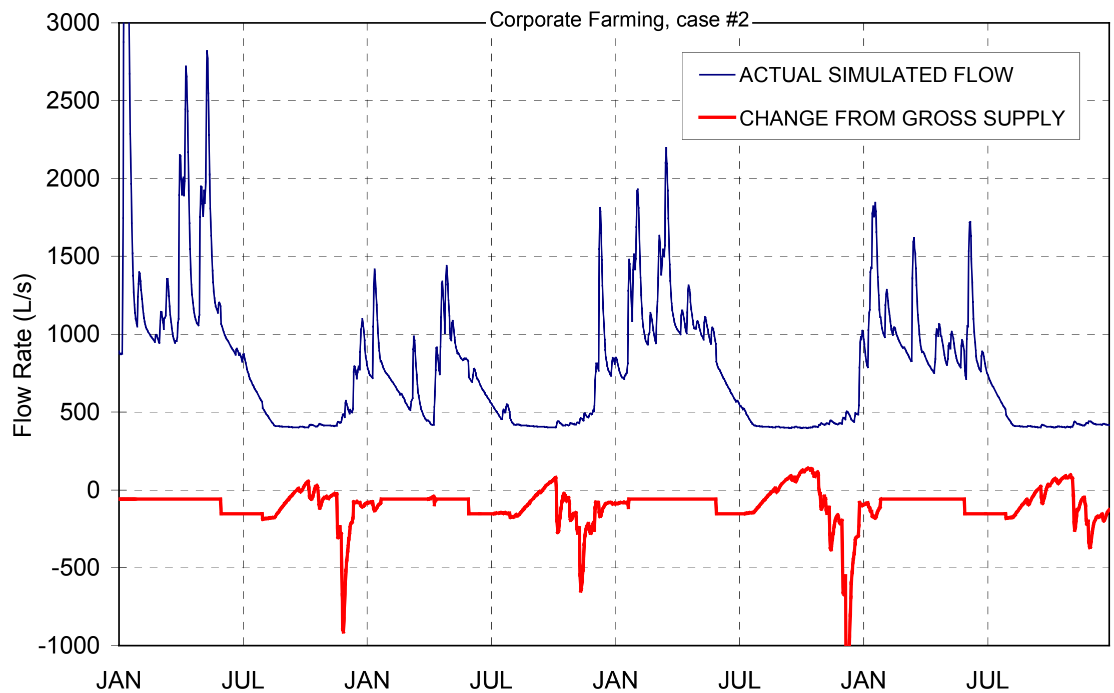



Figure 6-12. Simulated river flow (upper curve) and the change from gross river flow due to water use and impedance by dams (lower curve), for the Corporate Farming scenario with dams built in the river, for a period of 4 years.

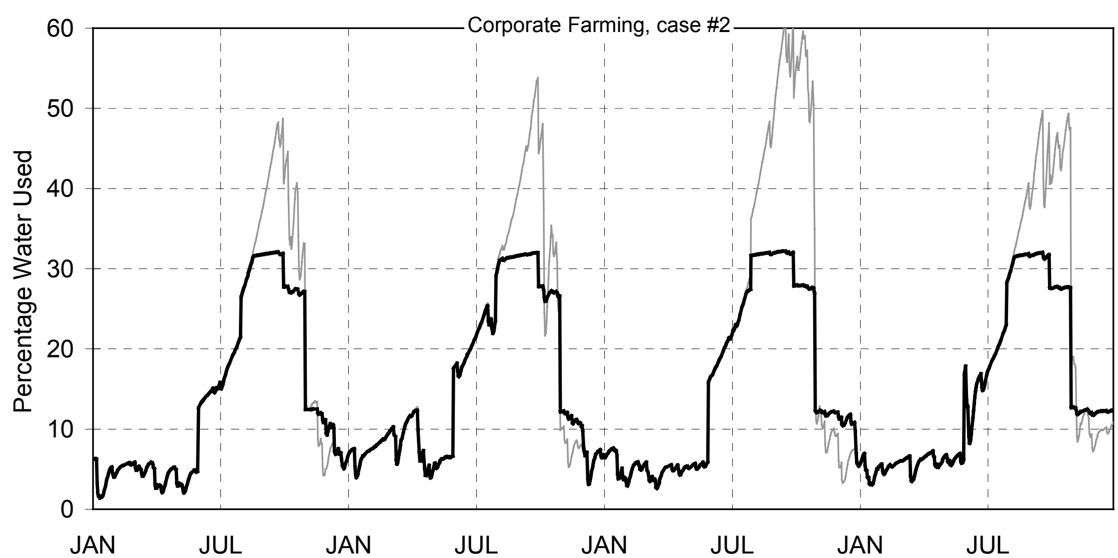



Figure 6-13. Simulated percentage of river flow that was extracted for direct use or refilling of dams, without dams built in the river (gray curve) and with dam (black curve), for the Corporate Farming scenario, for a period of 4 years.

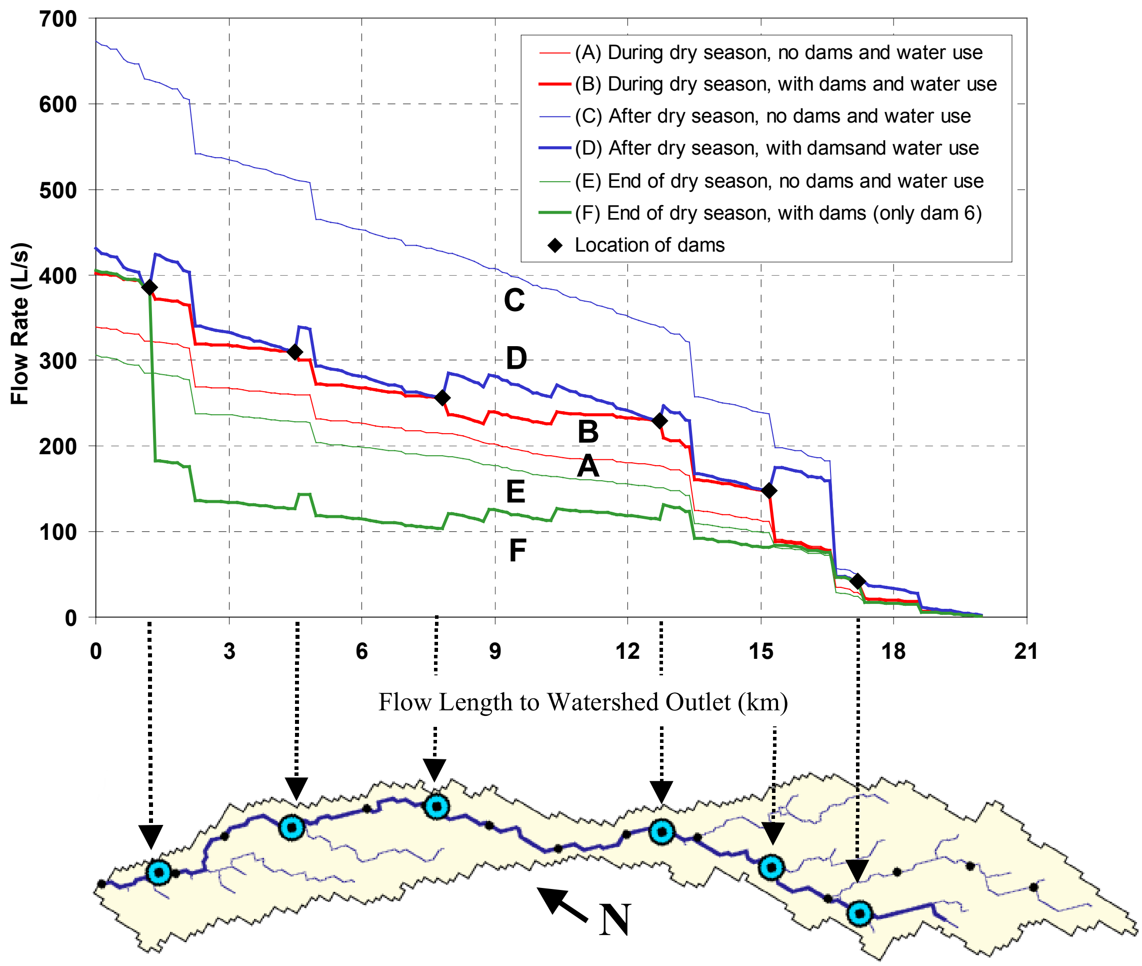



Figure 6-14. Simulated river flow as function of flow length to the watershed outlet, for the Corporate Farming scenario with dams built in the river, for a typical day in the dry season when all dams release water to sustain minimum flows, and a typical day shortly after the end of the dry season when storage in all dams increases.

Figure 6-14 demonstrates the effect that the dams had on river flow. Curve A indicates the river flow rate on a day in the dry season if no dams were present and no water were used. The flow rate at the outlet would have been below the required minimum of 400 L/s. Curve B shows the river flow rate on that day, accounting for water use and dams. On this particular day, all dams released part of the water in storage to sustain the minimum required flow rates at their locations (respectively 385, 310, 256, 229, 148 and 42 L/s). Curve C indicates the river flow rate on a day shortly after the end of the dry season if no dams were present and no water were used. Curve D shows the river flow rate on that day, accounting for water use and dams. Each dam reduced the river flow rate to the minimum required flow, using the surplus water to refill the dam. The two example dates were chosen to illustrate the combined effect of a simultaneous intervention by all six dams. This occurred only during short periods of the year (Figure 6-15).

Figure 6-15 shows the storage in each dam over the 4-year period. In contrast to the situation with dams as external reservoirs (Figure 6-11), there is a difference between the dams. The different minimum flow requirements and flow rates into each dam caused this difference. None of the dams ran empty during the first, second and fourth year. In the third year, however, the storage in four dams reached zero during one or more days. This did not happen to dam #6, the most downstream dam (although only 1.3% of storage capacity was left). Consequently, the flow requirement of 400 L/s at the watershed outlet could be met all year (see Figure 6-12). This is illustrated by curves E and F in Figure 6-14. Curve E indicates the river flow rate on a day at the end of the dry season if no dams were present and no water were used. Curve F shows the river flow rate on that day, accounting for water use and water release by dam 6 only.

The simulation results in Figure 6-15 were used to calculate the minimum combined capacity of the dams necessary to meet water demand and sustain minimum flow rate all year This was done for minimum flow requirements of 300, 350, 400, 450 and 500 L/s at the watershed outlet (Table 6-6). For the second year, the combined dam capacity of 1,800,000 m could have been decreased to as low as 741,000 $m^3$, whereas 1,725,000 $m^3$ capacity would have been necessary in the dry third year. These numbers were, respectively, 116% and 55% higher for a flow requirement of 500L/s rather than 400 L/s.

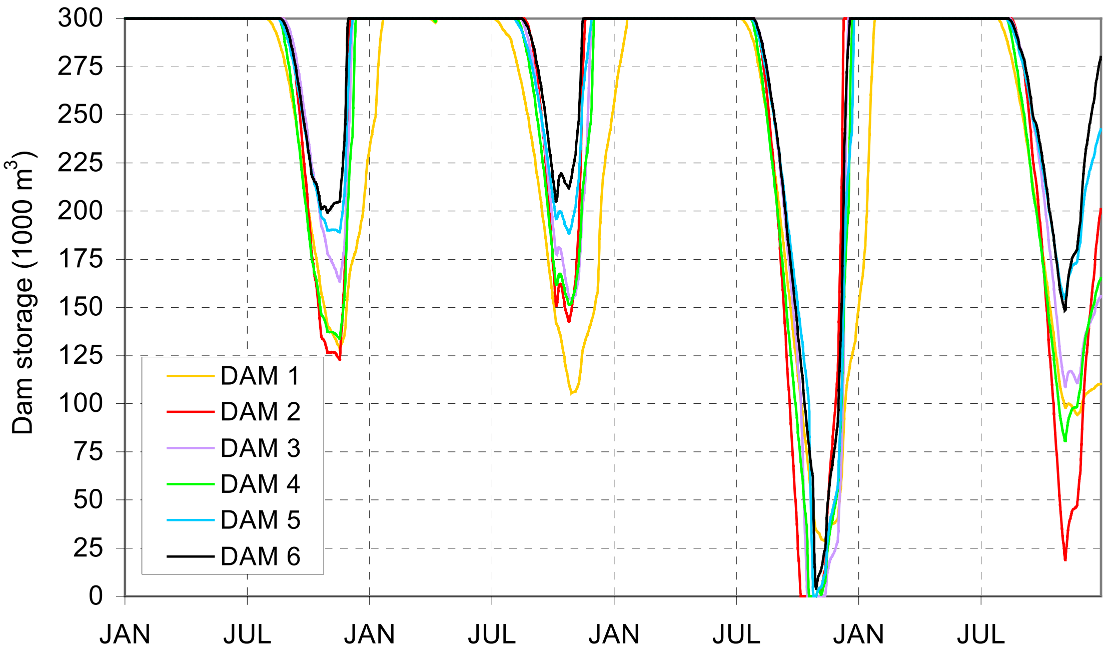



Figure 6-15. Storage in each dam, for the Corporate Farming scenario with dams built in the river. The dams are numbered in downstream direction (i.e. dam #6 is closest to the outlet).

Table 6-6. Minimum required combined capacity of the six dams to meet irrigation water demands and sustain minimum flow rates all year, for 5 different minimum flow rates.

| Minimum flow (L/s) | 300 | 350 | 400 | 450 | 500 |
|---|---|---|---|---|---|
| | ------------- Combined capacity of dams, in 1000 m$^3$ ------------ | | | | |
| Year 1 | 231 | 464 | 779 | 1193 | 1638 |
| Year 2 | 277 | 424 | 741 | 1133 | 1601 |
| Year 3 | 933 | 1320 | 1725 | 2170 | 2671 |
| Year 4 | 444 | 768 | 1133 | 1534 | 1983 |

Ecological Watershed Scenario

Figure 6-16 shows the simulated flow rate at the watershed outlet after considering water use and impedance by dams, as well as the change in river flow. The simulated flow rate was kept between the minimum required rate of 350 L/s and the maximum allowed rate of 1,500 L/s, except in January of the first year (over 200 mm rain fell within a week) and again in April (two consecutive periods with more than 150 mm rain each). The combined storage capacity of the dams was insufficient to adequately reduce the high peak flows that occurred.

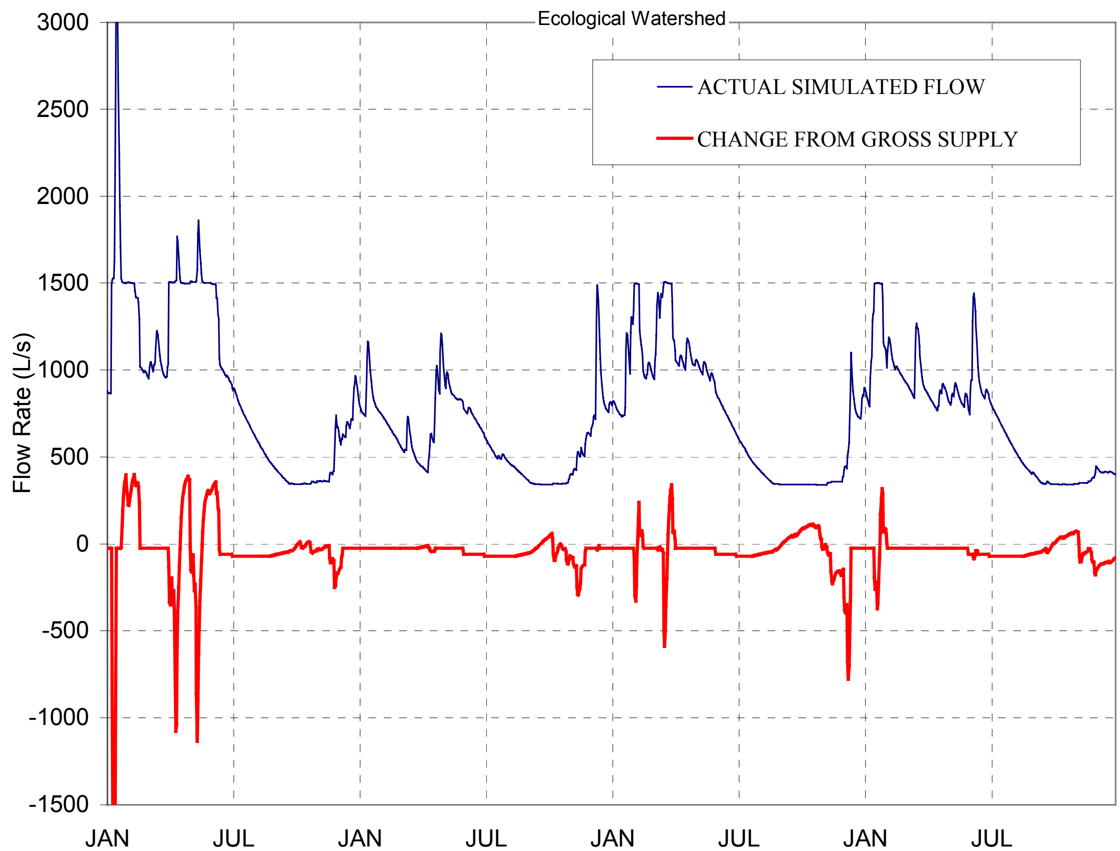



Figure 6-16. Simulated river flow (upper curve) and change from gross river flow due to water use and impedance by dams (lower curve), for the Ecological Watershed scenario, for a period of 4 years.

The negative changes in river flow in Figure 6-16 were caused by a net water intake by the dams. This occurred on days with peak flow rates above 1,500 L/s. Figure 6-18 (lower curve) shows how the change in river flow rate as a function of flow length to the watershed outlet. This curve applies to a particular day with a river flow rate of 1,860 L/s.

On the other hand, a positive change in river flow in Figure 6-16 reflects a net release of water from the dams. This happened in two different situations. First, immediately after rainy days, when flow rates dropped below the maximum allowed flow rate of 1,500 L/s. Dams had then accumulated a lot of water and released it until the water levels returned to the equilibrium level. Secondly, it occurred during the dry season, when water was released to sustain the minimum required flow rate. For a particular day in the dry season, Figure 6-18 (upper curve) shows the change in river as a function of flow length to the outlet.

Figure 6-17 shows the percentage of river water that was extracted for direct domestic, industrial, and agricultural use. The lowest and highest percentages were 0.9% and 16.9%, respectively. The maximum value of 16.9% is the lowest of all three scenarios (Table 6-5). Also, it is only a little higher than in 1989 (16.9 vs 15.5%, see Table 6-5), despite the fact that the irrigation water use increased from 1,503 $m^3d^{-1}$ in 1989 to 4,000 $m^3d^{-1}$ in the Ecological Watershed scenario. The dams and the minimum flow requirements are the reason for this. Without dams, the highest percentage of water use would have increased to 26.2%.

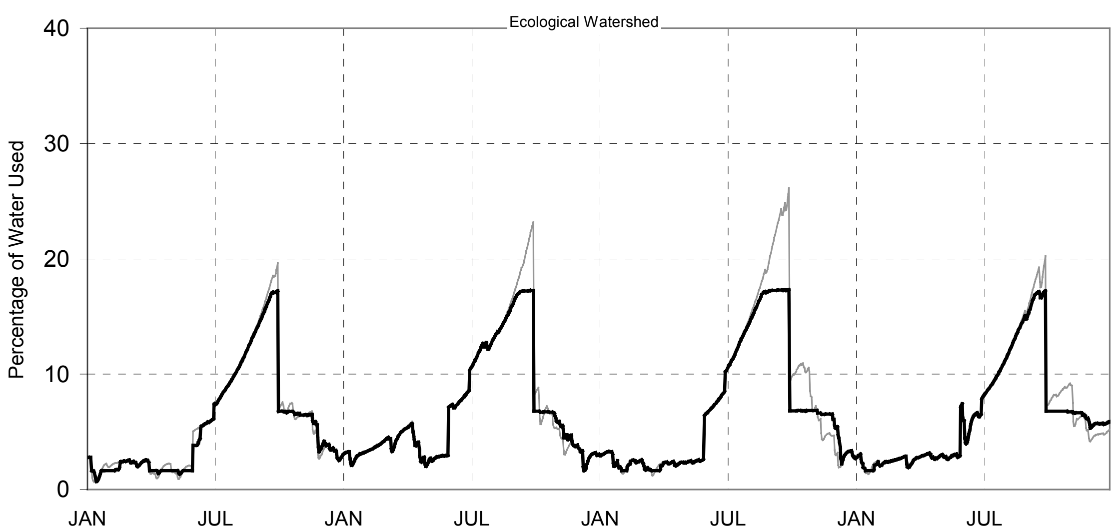



Figure 6-17. Percentage of river water extracted for direct use, without dams (gray curve) and with dams (black curve), for the Ecological Watershed scenario, for a period of 4 years.

Figure 6-19 shows the amount of water stored in each dam over the 4-year period. The equilibrium amount of storage was 50,000 $m^3$ in each dam. Storage increased during periods with high rainfall and peak flows above 1,500 L/s. Storage decreased during the dry season to sustain minimum required flow rates.

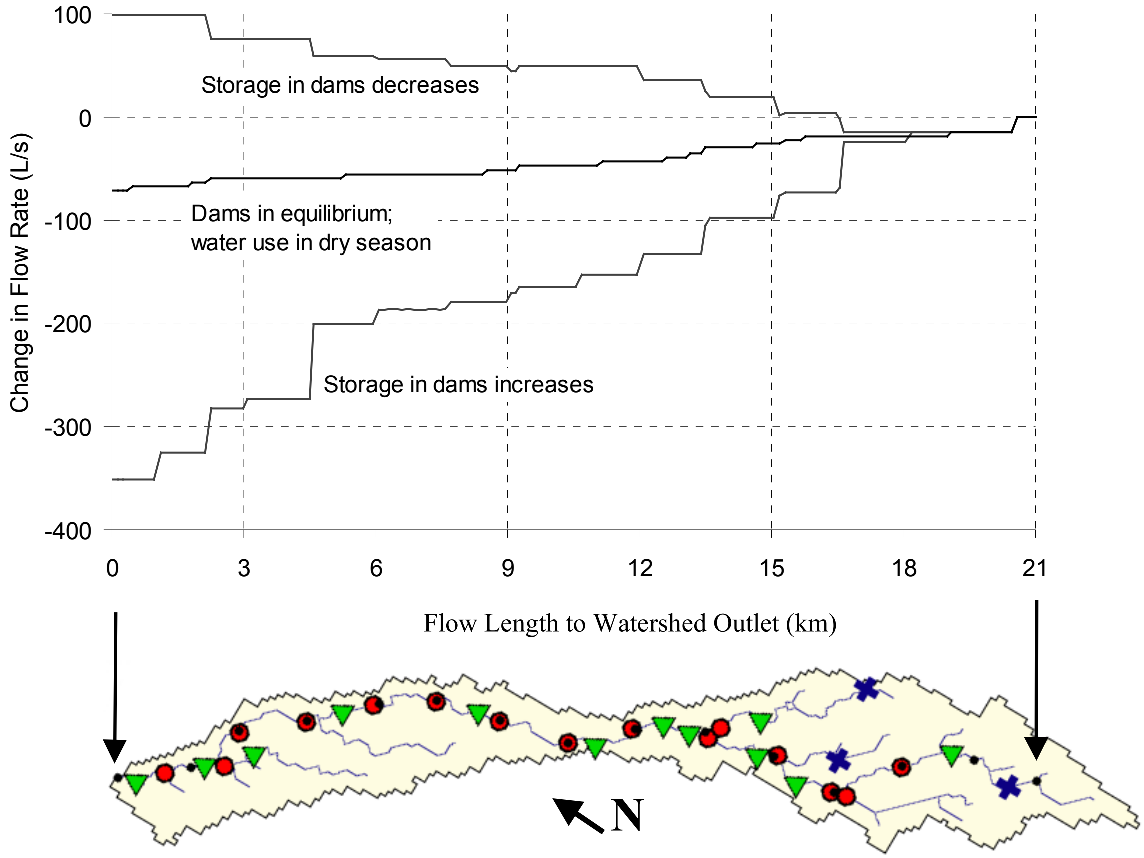



Figure 6-18. Simulated change in river flow due to water use and change of water storage in dams, as function of flow length to the watershed outlet, for the Ecological Watershed scenario. The flow length between the small black dots is 1.5 km.

<u>Business as Usual Scenario</u>

Figure 6-20 shows the simulated river flow at the watershed outlet after water use, as well as the change from gross river flow. In contrast to the other two scenarios, river flow showed high and frequent peaks caused by surface runoff. The change in river flow was relatively small because water use was low in this scenario.

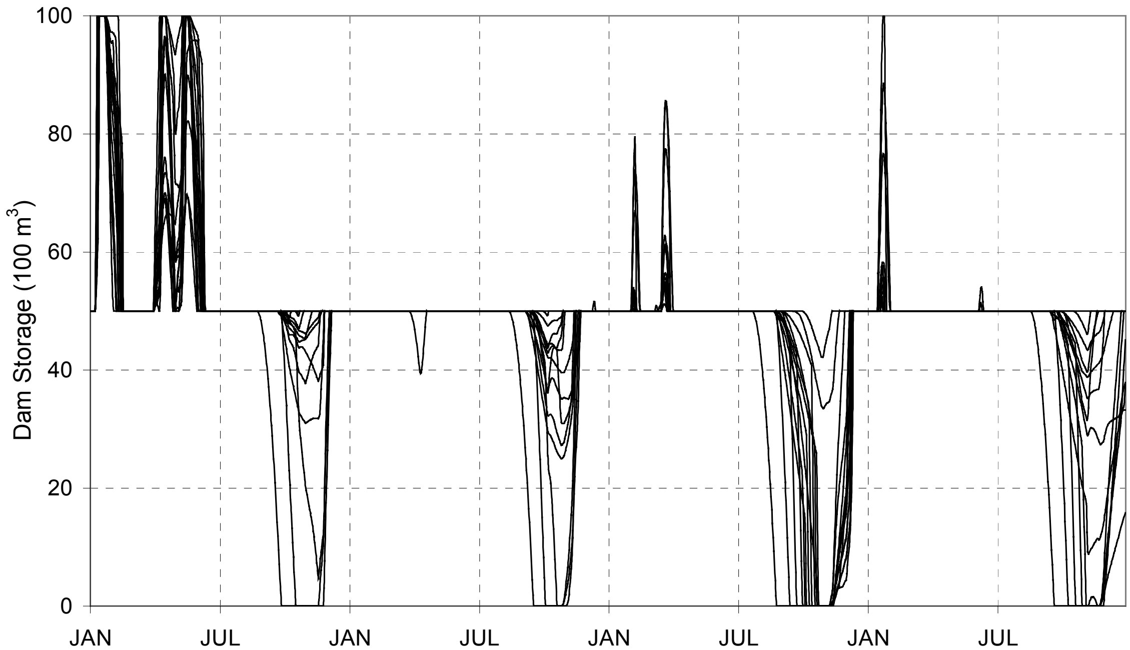



Figure 6-19. Amount of water stored in each dam during four simulated years, Ecological watershed scenario. There are 15 curves in this graph, one for each dam.

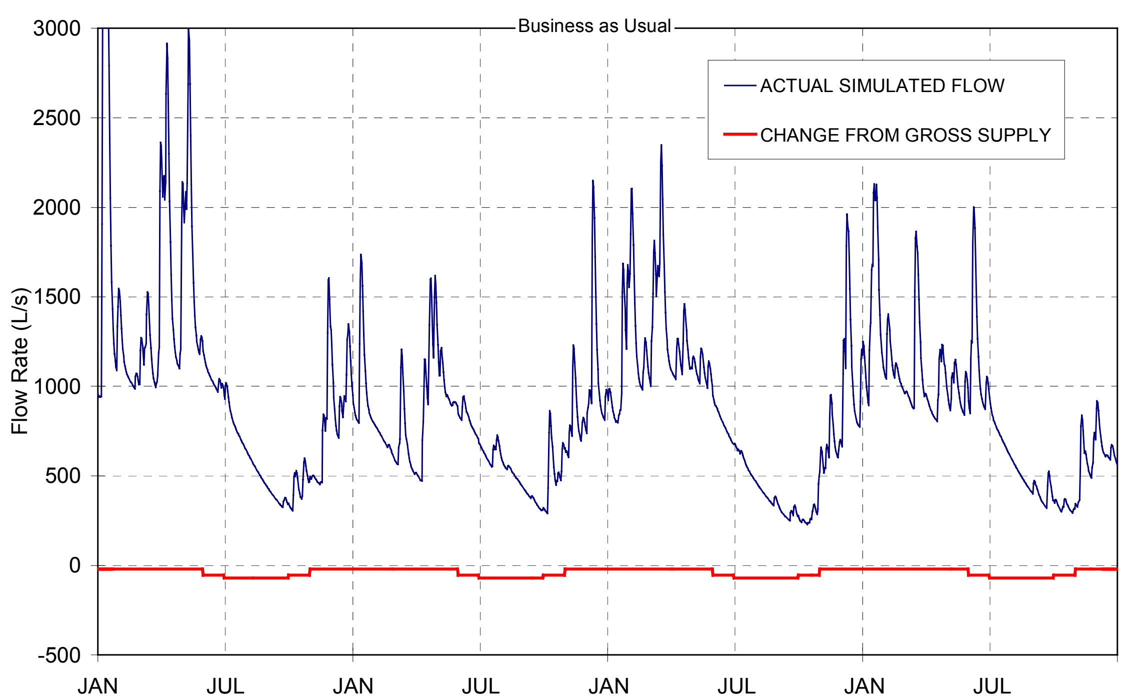



Figure 6-20. Simulated river flow (upper curve) and change from gross river flow due to water use (lower curve), for the Business as Usual scenario, for a period of 4 years.

The lowest and highest percentages of water extracted from the river were 0.67 and 21.9%, respectively (Figure 6-21). These percentages were considerably lower than those for the Corporate Farming scenarios (2.1% and 32.1%, respectively), which was caused by the combined effects of the much lower industrial and agricultural water use and higher stream flow before water extraction (Table 6-5). The maximum rate of water use differed little between the Business as Usual and Ecological Watershed scenarios (6,078 $m^3d^{-1}$ and 6,160 $m^3d^{-1}$, respectively). Nevertheless, the maximum percentage of water extraction was considerably larger for the former (21.9% vs. 16.9%), caused by absence of dams.

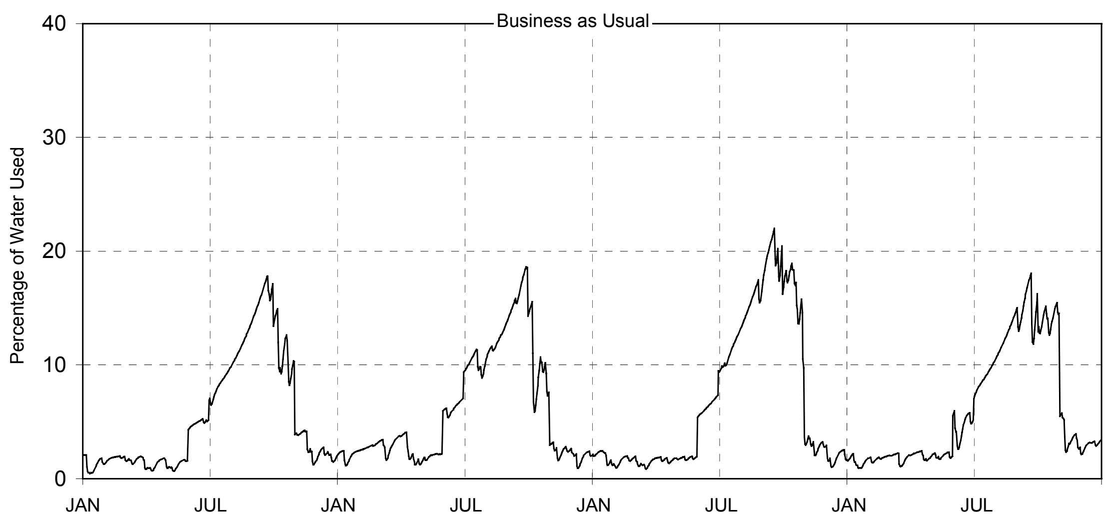



Figure 6-21. Simulated percentage of river flow that was extracted for direct use, for the Business as Usual scenario, for a period of 4 years.

Figure 6-22 shows the reduction in stream flow at different distance to the watershed outlet. Because there are no dams that could control river flow rates, only three specific levels of reduction in river flow occurred during a year. At the watershed outlet (0 km flow length), these levels correspond exactly to the three levels of water use shown in Figure 6-4. The difference between these levels is solely determined by the rate of irrigation.

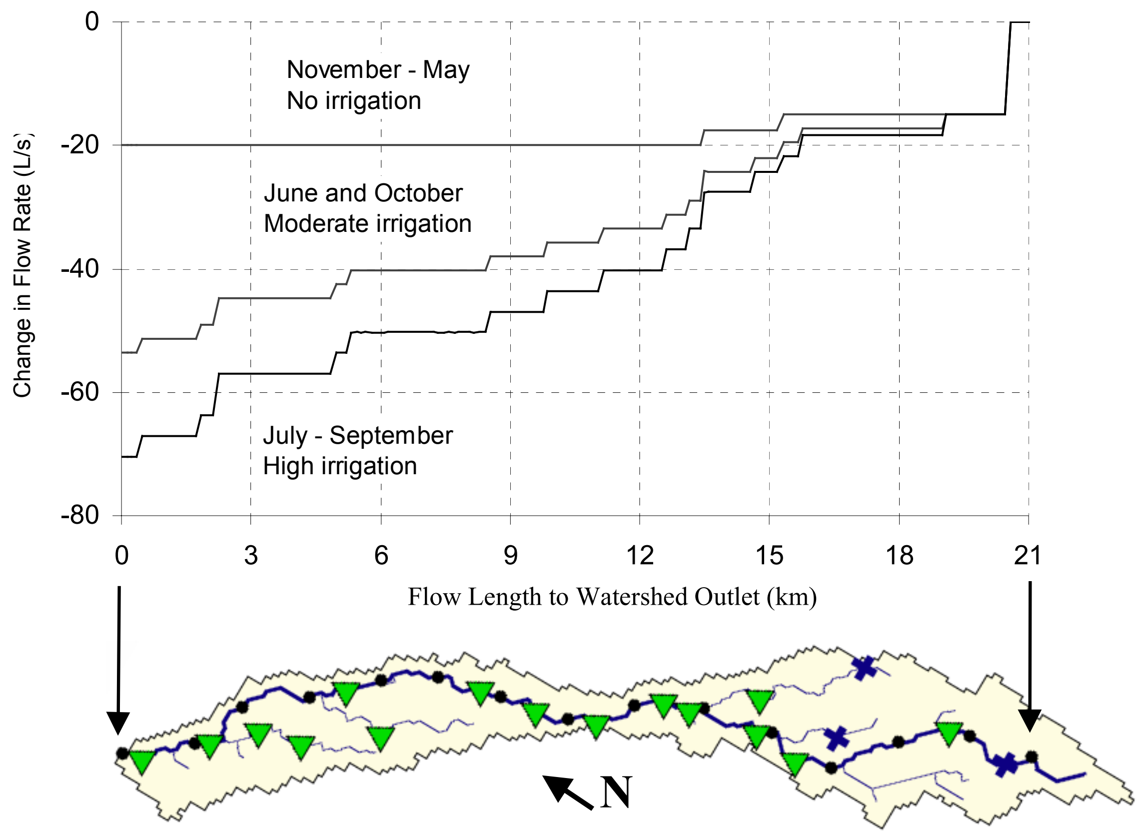



Figure 6-22. Simulated change in river flow due to water use, as a function of flow length to the watershed outlet, for the Business as Usual scenario. The flow length between the small black dots is 1.5 km.

Implications for Local Stakeholders

Local stakeholders in the Cabuyal River watershed have expressed concern about the negative effects of certain land use changes and poorly managed land on the hydrological response of the watershed. Several conflicts arose during the last decade about the overuse of water, resulting in water shortages in some parts of the watershed (Ravnborg and Ashby, 1996). A decrease in the average water yield, in combination with virtually unregulated use of water, may have serious consequences for downstream water availability. An important question regarding future development is then, what could policy makers do to avoid water shortages in the near future, and how can local communities be involved?

Several assumptions were made in this study. Dams were distributed evenly throughout the watershed and functioned properly. A perfect infrastructure for water transport to the 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 water at full capacity all year, unless supply in the river was insufficient. No limitations or technical difficulties in extracting water from the Cabuyal River and applying it for irrigation throughout the watershed were considered. Moreover, we did not consider in-situ use of water for recreation, fisheries, or dilution of any industrial waste products. These water uses are currently not important in the watershed.

Scenario results suggested neither a critical nor an ideal direction of development, but they could help navigate an acceptable path of development. The watershed has the potential to meet anticipated increase in water use, in particular more irrigation. For each of the three scenarios, it was possible to meet domestic, industrial and agricultural water demand at every day of the year, using water directly from the Cabuyal River or from dams. How can we then explain the current "early warning signs" of water scarcity?

A key issue is the correct interpretation of these early warning signs. Current water-related problems in the watershed seem to be related to water management practices, rather than the amount of available water. These management practices do not provide much leeway for the future, but they are correctable. Water availability is distributed in a temporally heterogeneous manner in patterns that differ from water needs, that is, a lot of water is available when it is not needed, and vice versa. It is important that policy makers together with local communities take proper action to ensure that sufficient water is available when and where the demand is highest. A number of specific issues will now be discussed.

Water yield of upper and lower part of watershed

Local people believe that the upper watershed tributaries determine the water flow in the Cabuyal River (Knapp et al., 1999). However, simulations indicated that the lower and upper parts of the watershed contribute equally to stream water supply. Simple mapping (delineating catchment areas from a DEM) can prove this too, roughly. Local stakeholders and policy makers should be aware of such basic spatial relationships within the watershed. Land use changes in the upper part of the watershed will affect water yield in the same way as a similar land use change in the lower part of the watershed. However, the upper and lower parts do differ in *how* they contribute to river flow, i.e. through surface runoff or base flow. Water and land management planning efforts could benefit from this knowledge on these spatial differences within the watershed.

Impact of land use change on the water yield.

Many local farmers consider forests as "water producers" (E.B. Knapp, 1998, personal communication) and are much concerned about the negative effects of deforestation and poor land management on availability of water in the streams. Deforestation means a loss of ground cover and will, consequently, result in more surface runoff and more erratic river flow with higher peak flows. This thinking was one of the reasons for a participatory research project in the watershed that was carried out in the early 1990, which involved the creation of protective areas around springs and streams using different plants (Ashby et al., 1996; E.B. Knapp, 1997, personal communication). Live barriers had other advantages as well, such as the prevention of erosion of stream beds, prevention of damage to water sources by land burning, and supply of useful materials (Ravnborg et al., 1996).

It is often incorrectly thought that forests increase water yield (Calder, 1998; Hamilton, 1985). Simulations for the Cabuyal River watershed indicated that this is not the case

(Table 6-4). The average annual river flow and the minimum base flow were highest for the Business as Usual scenario (when there was little forest) and lowest for the Ecological Watershed scenario (when there was more forest). While few will argue about the beneficial effects of reforestation and creating protective areas around streams and springs, there is no scientific evidence that such activities will result in *more* water in the Cabuyal River.

Use of the drinking water systems

Today, many problems and conflicts associated with water availability in the watershed seem related to the insufficient supply of drinking water to communities in the middle and lower zones. Concern about the diminished quantity or quality of water in river itself have not been reported yet. The problem with the drinking water systems is that too much of its water is used for irrigation during the dry months. This is an illegal practice, but it is neither monitored nor enforced. Consequently, there is little incentive for farmers to change towards more cumbersome and costlier irrigation methods such as the use of water directly out of a stream. That would require investment in a water pumps and construction of pipes.

The current drinking water systems with a combined capacity of 30 L/s, however, cannot possibly supply sufficient water to meet both domestic and agricultural water needs during the dry season. The drinking water system committees (JAAs, *Junta Administradora del Aqueducto*) should provide proper development for their use. First, the JAAs should claim water rights to prevent future problems with water allocation, as suggested by de Fraiture et al. (1997). Secondly, they have to ensure that the drinking water is exclusively used for domestic purposes and monitor its use. Such measure would likely generate a lot of opposition from farmers who currently use drinking water for irrigation. These farmers should be given financial and/or technical assistance for exploiting other sources of irrigation water, in particular by pumping it directly out of a stream. Thirdly, a continuous supply of water at the capacity of the systems must be ensured. This can be ensured by, among others, adequate and prompt repair of leaks and frequent cleaning of water filters (removing leaves and twigs). And fourthly, the infrastructure of the drinking water systems should be improved so that all households have access to it.

Assuming this can be achieved, the current 30 L/s capacity of the drinking water systems would be adequate to meet even the high domestic water demands for the Business as Usual scenario in 2025. Suppose that industries and farmers were allowed (if it were legalized) to continue using water from the drinking water systems. Total water demand (including irrigation) in the Ecological Watershed and Business as Usual scenarios could be met all year by the drinking water systems if their combined capacity were increased to 80 L/s. However, this situation would not offer much leeway for increased irrigation application during periods of extreme drought, or if all farmers decided to irrigated at the same time. The 80 L/s capacity would be insufficient to supply enough irrigation water in the Corporate Farming scenario.

Construction of dams and reservoirs

Construction of large basins seems the best alternative to supplying enough irrigation water without endangering water supply to households and industries. These basins can be constructed as reservoirs external to the river or as dams built in the river. The latter would also allow controlling minimum flow rates during the dry season, which could be useful or necessary for at least two reasons. First, at some point in the future the Cabuyal River may contribute to the water supply to an existing hydropower plant (this was part of the description of the Ecological Watershed scenario, Appendix E). Authorities may require a minimum water flow rate to ensure power supply. Secondly, a minimum flow rate may be desirable to sufficiently dilute any industrial waste products or contaminants in the river.

The data in Table 6-6 illustrated that the required combined capacity of dams depends on the minimum flow requirement and also significantly varied from year to year. There is currently neither a dam nor any plan for construction of one the Cabuyal River watershed. However, planners in 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 thousand families (E.B. Knapp, 1999, personal communication). No detailed information was available on the specific objectives and operation of this dam, anticipated water extraction from it, and any minimum river flow rates that this dam would have to maintain. However, the volume of this dam is equivalent to a dam with a capacity of 0.45 million $m^3$ to support the 1,250 families in the Corporate Farming scenario in the Cabuyal River watershed. This dam capacity compares well to those calculated for the 300 and 350 L/s flow requirements in Table 6-6.

## Conclusions

Simulation results indicated that the Cabuyal River watershed has the potential to meet the anticipated increases in water use in the near future. It was possible to meet the domestic, industrial and agricultural water demand at every day under each of the three scenarios, using water directly from the Cabuyal River or from dams.

Proper management of water resources and effective institutional arrangements were assumed. However, even if such ideal conditions were in place in reality, it may be unacceptable to use a high percentage of the available water during part of the year. It characterizes an ecosystem that has little resilience to sudden increases in water demand and one that does not provide for *in-situ* use of water for recreation, fisheries, or dilution of any industrial waste products. Therefore, extraction of a large amount of water, such as up to 61% in the Corporate Farming scenario if there were no dams, is worrisome and could be a serious problem.

Construction of dams seems the best method to supplying sufficient irrigation water without endangering water supply to industries and households. SWBM was a useful tool to determine the storage capacity of dams needed to serve three purposes: irrigation water supply, reducing peak flow rates, and sustaining minimum flow rates. Minimum flow rates also helped reduce the maximum percentage of the river flow that was extracted at any particular day. Because of the small capacity of the current drinking water systems in the Cabuyal River watershed, they should be used to exclusively supply water for domestic use.

The choice of the scenarios and the results of the analyses suggested neither a critical nor an ideal direction of future development. All three scenarios are plausible but it is unlikely that the watershed will end up exactly as one of the scenarios. The scenarios could, however, characterize part of the whole and help navigate an acceptable path of future development. Local communities should collectively manage their water resources and design a set of institutional arrangements that help build the future for the Cabuyal River watershed.

CHAPTER 7
SUMMARY AND CONCLUSIONS

This study presented a tool for community-based water resources management in hillside watersheds. It was used to study the implications of different directions of development on water availability in the Cabuyal River watershed, southwest Colombia. The study consisted of several research activities that were described in separate chapters. This chapter summarizes briefly the conclusions of each phase of the study.

A simulation-based framework was presented for assessing water scarcity on a watershed scale under different paths of development. Water scarcity was evaluated by looking at stream water availability throughout the watershed, the reduction in stream flow after water use, the percentage of the river flow that was used, what time of the year critical water shortages occurred, and the locations where the risk for water shortages seemed greatest.

The Spatial Water Budget Model (SWBM) was developed for simulating water use and water supply on a watershed scale and analyzing temporal and spatial variations in the overall water balance and in stream water flow under different land use, population growth, industrial development, irrigation water demand, and operations of dams. SWBM was in particular designed for use in hillside watersheds of Latin America and the Caribbean. The model was a tradeoff between hydrological detail and usefulness as a tool for assessing water scarcity and identifying break points in watershed behavior. Rather than detailing the movement of soil water, SWBM's strength is in the accounting of stream water throughout the watershed, including water use from streams and impedance by dams. The simplified drainage and lateral flow model was developed to easily calculate lateral flow to streams in a hillside watershed that has a complex and heterogeneous landscape.

Simulated flows rates of the Cabuyal River from 1994 through 1997 compared well to measured flow rates and varied significantly over space and time. On average 81% of the simulated river flow was base flow. The simplified drainage model gave estimates of drainage out of a single hill slope that were very close to those approximated with the theoretical Darcy model. Simulated drainage rates for the watershed as a whole were similar to base flow rates that were derived from long-term daily measured flow rates of the Ovejas River.

The hydrological response of the Cabuyal River watershed with uniform bare soil, forest, and cropped land was very different. A bare soil resulted in annual high surface runoff and river flow but relatively little base flow, whereas a forest land cover gave low annual surface runoff and less river flow but more base flow. Annual river flow with bare soil was 49% higher than the 4-year average for the calibrated model (824 L/s), with cropland 5% higher, and with forest 14% lower. The significant difference in base flow index of the lower and upper parts of the watershed, respectively 0.759 and 0.867, indicated that these parts differ in *how* they contributed to river flow. This was caused by differences in land use.

Daily domestic and industrial water use in the administrative Cabuyal region during the years 1994-1997 was quantified based on per capita water demand and knowledge about the production processes of local industries. The amounts of water used by households and industries were relatively small compared to irrigation water requirements. The latter were estimated for a tomato crop using a crop simulation model. Water demands were distributed in a temporally heterogeneous manner in patterns that differ from water availability, that is, much water was available when it was not needed, and vice versa.

According to a water availability classification used by local planning agencies in the province of Cauca, simulated water availability in the Cabuyal River watershed was *low* or *very low* during approximately half of each year. Nevertheless, simulation results indicated that there was sufficient water in the Cabuyal River to meet the estimated water demands at any day from 1994 through 1997. The reduction in river flow by water use was up to 16% in the dry season. Three dams with a storage capacity of 1 million $m^3$ each helped sustain a minimum flow rate of 350 L/s and a maximum rate of 1,500 L/s at the watershed outlet.

Current complains about reduced or insufficient water availability in the watershed seem related to the fact that the drinking water systems are used as a source of irrigation water, but they were not designed for this purpose. Estimated irrigation water requirements in August were nearly twice the combined capacity of the drinking water systems and could, therefore, impossible be supplied by them. To solve these problems, local decision-makers could consider increasing the capacity of the drinking water systems or helping farmers exploit other sources of irrigation water, in particular by pumping it directly out of a stream

A generic, rule-based land use change model was developed to generate land use patterns for any number of years in the future. The model was used to create three plausible land use grids for the Cabuyal River watershed in 2025, which were needed to simulate three scenarios with the SWBM model. These scenarios described contrasting but plausible views of the future of the Cabuyal River watershed in 2025. The direction of land use change under each scenario was based on relative tendencies to move from one land use type to another. These relative tendencies, which were different for each scenario, accounted for how land use changes might occur with respect to six spatially variable characteristics of the landscape. These relationships were assumed constant, i.e. dynamics in land use drivers was not accounted for. Simulated land use evolved in a plausible fashion. After a long period of time, the distribution of land use reached a near-equilibrium. This was a result of using fixed relative tendencies. The percentage of the area that was covered by each land use type (bare soil, crops, scrub, pasture and forest) after 36 simulated years was different for each scenario.

The scenario results suggested neither a critical nor an ideal direction of development, but they could help characterize part of the whole and help navigate an acceptable path of future development. The Cabuyal River watershed has the potential to meet the anticipated increases in water use, particularly more irrigation. It was possible to meet domestic, industrial, and agricultural water demands at any day under each of the three scenarios, using water directly from the river or from dams. However, extraction of a large amount of water from the river, such as up to 61% in August under the Corporate Farming scenario if there were no dams, is worrisome and could be a serious problem.

The results of the scenario analyses have important practical implications for local communities and decision-makers. Current water-related problems seem related to water management practices, rather than the amount of available water. These practices do not provide much leeway for the future, but they are correctable. Simulation results suggested a number of specific water management measures that could be taken. Because of the small capacity of the drinking water systems, they should be used for domestic purposes only. Local-level management organizations should provide proper development for the use of these systems. Construction of dams seems the best method to supplying enough irrigation water without endangering water supply to households and industries. Dams could also be used to control river flow rates, in particular to maintain a minimum flow rate, which may be desirable to sufficiently dilute any industrial waste products or for future hydro power generation. Land conservation practices, in particular deforestation, could change surface runoff and base flow characteristics, but annual water yields may not always be affected.

# APPENDIX A
# CHARACTERISTICS OF GIS-EMBEDDED MODELING

## What is GIS-embedded Modeling?

GIS-embedded modeling refers to the fact the programmer makes use of the intrinsic modeling capabilities of a Geographical Information System (GIS). This is an alternative to linking a model externally to the GIS (either through a loose or tight linkage). The user interacts directly with the GIS and the model; no data conversion between model and GIS databases is required. There are three ways to embed model equations in a GIS: (a) by modifying the source code of the GIS, (b) by writing macros to perform iterative sequences of map algebra calculations, and (c) by programming the model in a special programming or scripting language that is part of the GIS software. An example of such scripting language is Avenue, which is part of the ArcView GIS software (ESRI, 1996).

## Advantages of GIS-embedded modeling

1. Topographic data as well as other spatially variable data can be directly used from a raster or vector data set without any form of reformatting or conversion. Also, output data generally do not require any reformatting prior to mapping.
2. Spatial data need to be stored only once. This reduces the required storage space, is less error-prone and does not require any data conversion programs.
3. GIS is used for something else than just data storage and mapping.

4. Grid algebra is potentially tremendously powerful. Comprehensive spatial and statistical analysis, using spatially variable data or processes can easily be performed. This may be cumbersome or even impossible using a traditional programming language.
5. The number of lines of code in AML or Avenue may be considerably less than for an identical operation programmed in, for example, C or Fortran.
6. The model is platform independent in that it can be executed on any platform that the GIS can. ArcView GIS and ARC/INFO run under the Windows and Unix operating systems.

## Disadvantages of GIS-embedded Modeling

1. Embedded modeling precludes the use of well-tested, well-calibrated and widely accepted environmental models. GIS-embedded models are a new generation.
2. The model is not a single executable but a set of interpretable scripts (Avenue or AML). This may complicate the distribution of the model. However, a set of Avenue scripts can be grouped together in an ArcView project or user extension, which can be distributed as a single file. This is not possible with AML scripts.
3. GIS-embedded models may be computationally less efficient than external models. Execution of an interpreted language like Avenue is generally slower than execution of a compiled model. Moreover, temporary GIS data sets are always written to the hard disk rather than keeping them in memory, which may slow down the model execution significantly (hard disks are considered the slowest parts of computer systems).
4. In general, GIS-embedded models are less suitable for optimization and Monte Carlo simulations. This depends to some degree on the nature and complexity of the model, as well as the way it has been programmed.

APPENDIX B
HYDROLOGIC ANALYSIS IN GIS

A few relatively simple concepts are at the basis of GIS-based hydrological analysis. These concepts are a Digital Elevation Model, Flow Direction, Flow Accumulation, Stream Network Delineation, Flow Length and Sub-watershed Delineation. Detailed information on conducting these hydrological analyses using ARC/INFO and ArcView GIS software can be found in ESRI (1994, 1996b). The different analyses have been illustrated for a hypothetical area of 6 by 6 grid cells. Examples of programming code are given in the Arc Macro Language (ESRI, 1997c) and Avenue (ESRI, 1996a). A reference manual of these programming languages should be consulted for details on the full syntax of the language.

The coding convention is as follows: ARC/INFO and Avenue commands are indicated in **BOLD CAPITALS**, variables for spatial grids in *italic*, and other command line arguments in normal characters.

## Digital Elevation Model

A Digital Elevation Model (DEM) is a raster representation of a continuous surface, usually referring to the surface of the Earth. A DEM is the primary data set required for GIS-based (surface) hydrologic analysis and is usually created from digitized topographic maps or from special air photography. A DEM may contain topographic heights or sinks, also referred to as depressions. They may be a true representation of the local topography. However, the presence of sinks is particularly problematic for flow analysis because the water that flows in cannot flow out. This results in an erroneous Flow Direction grid. Therefore, sinks must always be removed by increasing the elevation at their location to a level equal to that of the lowest adjacent grid cell. This process is referred to as "filling sinks". It is an iterative process because filling a sink may create another sink. This iteration is automatically performed using a single AML command. However, in Avenue it more complicated because a series of commands must be used and the iteration process must be programmed manually. The Avenue example below shows the commands for one iteration step only. By replacing *raw_dem* with the new *filled_dem* (which may not yet be completely free of sinks), the series commands can be repeated. Two to four iterations are generally sufficient.

AML: **FILL** *raw_dem filled_dem* SINK

Avenue: *flowdirection* = **FLOWDIRECTION** (*raw_dem*)

*temp1grd* = *flowdirection*.**WATERSHED** (*flowdirection*.**SINK**)

*temp2grd* = *temp1grd*.**ZONALFILL** (*raw_dem*)

*temp3grd* = *temp2grd*.**ISNULL.CON** (0.AsGrid, *temp2grd*)

*filled_dem* = (*raw_dem* < *temp3grd*). **CON** (*temp2grd*, *raw_dem*)

## Flow Direction

The direction of surface flow of each grid cell is the direction of steepest decent. There are 8 possible directions, relating to the eight adjacent cells into which flow could travel. These are indicated with the digital numbers 1, 2, 4, 8, 16, 32, 64 and 128, which correspond to the directions E, SE, S, SW, W, NW, N and NE, respectively. Any numbers other than these eight that appear in a Flow Direction grid indicate that the DEM was not depressionless. A DEM is the only data set that is required for deriving the flow direction.

AML: *flowdirection* = **FLOWDIRECTION** (*filled_dem*)

Avenue: *flowdirection* = *filled_dem.***FLOWDIRECTION** (FALSE)

Flow Accumulation

This is the accumulated weight of all grid cells flowing into each downstream grid cell. If no weight is provided, a weight of 1 is applied to each grid cell, and the value of cells in the output grid will be the number of cells that flow into each cell. A possible weight could be the amount of rainfall (in m water depth) that falls on each grid cell. If this amount is multiplied with the area of a grid cell (in $m^2$), then the accumulated flow is the total volume of water (in $m^3$) that passed a grid cell. This is the basic principle of determining the daily water yield of a watershed. A weight of 1 has been used in the coding examples below.

AML: *flowaccumulation* = **FLOWACCUMULATION** (*flowdirection*, 1)

Avenue: *flowaccumulation* = *flowdirection.***FLOWACCUMULATION** (1.AsGrid)

Stream Network Delineation

A stream network can be delineated from a DEM by applying a threshold to the Flow Accumulation grid. Flow Accumulation in its simplest form is the number of upslope cells that flow into each cell. If the cell size is known, an area-based threshold can be applied. And if the Flow Accumulation represents a flow volume, a volume-based threshold can be applied. In the example below, a threshold of 25 grid cells has been used. All streams cells are assigned the value 1, and all other grid cells the value 0. These values can be chosen differently depending on the user's preferences or desired outcomes.

AML: *streamnetwork* = **CON** (*flowaccumulation* > 25, 1, 0)

Avenue: *streamnetwork* = (*flowaccumulation* > 25.AsGrid).**CON (**1.AsGrid, 0.AsGrid)

## Flow Length

If no specific weight is assigned to each grid cell, the flow length is the length of the flow path from each grid cell to the nearest sink, expressed in map units. Alternatively, some weight grid can be specified to define the impedance to move through each grid cell. Such weight grid could represent, for example, the hydraulic conductivity of the soil throughout the watershed, or the effort--which could be a function of slope--required to 'move through' the grid cell. In most cases we are interested in finding the flow length to the nearest stream or to the outlet of the watershed. In the first case all stream cells are considered sinks, while in the latter case only the grid cell with lowest elevation is considered a sink. A sink is indicated by a value of 255 for the flow direction (this is the sum of the eight other flow direction values). Flow lengths can be calculated in downstream or upstream direction. In the example below I calculate the downstream flow length and do not specify a weight.

Flow length from all grid cells (including stream cells) to the watershed outlet:

AML: *flowlength* = **FLOWLENGTH** (*flowdirection*, #, downstream)

Avenue: *flowlength* = *flowdirection*.**FLOWLENGTH** (nil, false)

Flow length from all grid cells (including stream cell) to the nearest stream cell:

AML: *flowdirection2* = **CON** (**ISNULL** (*streamnetwork*), *flowdirection*, 255)

*flowlength* = **FLOWLENGTH** (*flowdirection2*, #, downstream)

Avenue: *flowdirection2* = *streamnetwork*.**ISNULL**.**CON** (*flowdirection*, 255.AsGrid)

*flowlength* = *flowdirection2*.**FLOWLENGTH** (nil, false)

Sub-Watershed Delineation

This refers to the division of a watershed in smaller basins (sub-watersheds) based on natural flow characteristics. A sub-watershed is the contributing area of a single branch of the stream network. Generally, if a larger threshold value for the stream network delineation is used, the stream network will consist of fewer branches. The number of sub-watershed will then also be less but their average size of the sub-watershed will be larger. For correct sub-watershed delineation it is important that all stream cells in the stream network grid have the same value (it does not matter what value) and all other cells the Null[2] value.

AML: *new_streamnetwork* = CON (*streamnetwork* > 0,0, setnull(1))

*subwatersheds* = **WATERSHED** (*flowdirection, new_streamnetwork*)

Avenue: *streamnetwork2* = (*streamnetwork* > 0).**SETNULL** (0.AsGrid)

*streamlinkgrid* = *streamnetwork2*.**STREAMLINK** (*flowdirection*)

*subwatersheds* = *flowdirection*.**WATERSHED** (*streamlinkgrid*)

---

[2] The Null value, also referred to as the 'No Data' value, is different from the number zero. The latter is a valid number, the former not. *Null* is assigned to cells in ARC/INFO grids if insufficient information about the particular characteristics of the location of that grid cell is available, or to indicate whether or not some characteristic is present or relevant at a specific location. *Null*, as meaningless as it may appear, can be used as a logical operator and allows sophisticated spatial analysis in GIS (the ISNULL and SETNULL commands are used several times throughout the Avenue coding examples).

(a) Digital Elevation Model

| | | | | | |
|---|---|---|---|---|---|
| 78 | 72 | 69 | 71 | 58 | 49 |
| 74 | 67 | 56 | 49 | 46 | 50 |
| 69 | 54 | 44 | 37 | 36 | 48 |
| 64 | 58 | 55 | 24 | 31 | 21 |
| 68 | 61 | 47 | 21 | 16 | 14 |
| 74 | 58 | 34 | 12 | 10 | 12 |

(b) Flow Direction

| | | | | | |
|---|---|---|---|---|---|
| 2 | 2 | 2 | 2 | 4 | 4 |
| 2 | 2 | 2 | 4 | 4 | 4 |
| 1 | 1 | 2 | 4 | 2 | 4 |
| 64 | 64 | 2 | 2 | 2 | 4 |
| 2 | 2 | 2 | 2 | 4 | 4 |
| 1 | 1 | 1 | 1 | 4 | 16 |

(c) Flow Accumulation

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 1 | 2 | 0 |
| 0 | 3 | 6 | 4 | 4 | 0 |
| 0 | 0 | 0 | 12 | 0 | 6 |
| 0 | 0 | 0 | 1 | 13 | 8 |
| 0 | 2 | 4 | 6 | 35 | 2 |

(d) Stream Network Delineation

| | | | | | |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 1 | 1 | 1 | 2 | 0 |
| 0 | 3 | 6 | 4 | 4 | 0 |
| 0 | 0 | 0 | 12 | 0 | 6 |
| 0 | 0 | 0 | 1 | 13 | 8 |
| 0 | 2 | 4 | 6 | 35 | 2 |

(e) Downstream Flow length

| | | | | | |
|---|---|---|---|---|---|
| 2.8 | 2.8 | 3.4 | 3.8 | 3.4 | 3.0 |
| 2.4 | 1.4 | 1.4 | 2.0 | 2.4 | 2.0 |
| 2.0 | 1.0 | 0.0 | 1.0 | 1.4 | 1.0 |
| 3.0 | 2.0 | 2.8 | 0.0 | 1.4 | 0.0 |
| 3.4 | 2.4 | 1.4 | 1.4 | 0.0 | 0.0 |
| 3.0 | 2.0 | 1.0 | 0.0 | 0.0 | 1.0 |

(f) Sub-Watershed Delineation

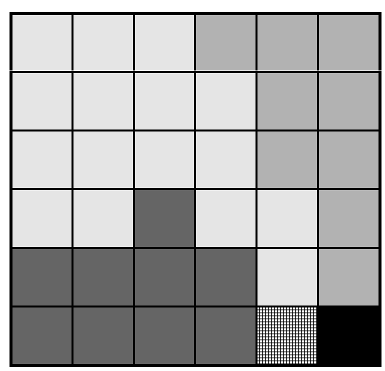


Figure B-1: Schematic representation of six basic concepts of GIS-based hydrological analysis, illustrated for 6x6 grid. a) Digital Elevation Model, with elevation typically expressed in feet or meters; b) Flow Direction, expressed as the number-equivalent of eight wind directions, c) Flow Accumulation, expressed as number of receiving grid cells; d) Stream Network Delineation, using a threshold of 5 grid cells; e) Downstream Flow Length to nearest stream cell, assuming a unit cell width; f) Sub-Watershed Delineation, resulting in four sub-watersheds. The smallest sub-watershed is just 1 cell large.

# APPENDIX C
# NOMENCLATURE

This appendix lists the symbols, descriptions and units of all variables that have been used in the descriptions of the simplified drainage and lateral flow model (Chapter 2), the Spatial Water Budget Model (Chapters 3 and 4), and the land use change model (Chapter 5).

| | | |
|---|---|---|
| $A_j$ | Initial canopy interception, land unit j. | mm |
| $A_{ref}$ | Reference initial canopy interception (at CF=1), per LU type. | mm |
| $AET_j$ | Actual evapotranspiration, land unit j. | mm $d^{-1}$ |
| $AK_j$ | Average hydraulic conductivity along flow path of land unit j. | m $d^{-1}$ |
| AREA | Size of a land unit (same for all land units). | $m^2$ |
| $B_j$ | Canopy interception gradient, land unit j. | [-] |
| $B_{ref}$ | Reference canopy interception gradient (at CF=1), per LU type. | [-] |
| $CF_j$ | Crop coefficient, land unit j. | [-] |
| CFSW | Soil water content depletion fraction, per land use type. | [-] |
| $CI_j$ | Canopy interception storage, land unit j. | mm |
| $CN_j$ | SCS curve number, land unit j. | [-] |
| $CN_I$ | SCS curve number for antecedent moisture conditions I. | [-] |
| $CN_{II}$ | SCS curve number for antecedent moisture conditions II. | [-] |
| $COR_{FL,j}$ | Drainage correction factor for flow length, land unit j. | [-] |
| $COR(X)_{SW,j}$ | Drainage correction for water content, comp. X, land unit j. | [-] |
| $CRIT_j$ | Critical soil water content in root zone, land unit j. | $m^3m^{-3}$ |
| $D_j$ | Drainage of water from root zone to deeper soil, land unit j. | mm $d^{-1}$ |
| $DLAYR_j$ | Thickness of soil root zone, land unit j. | m |
| $DRAIN_j$ | Drainage out of soil root zone, land unit j. | mm $d^{-1}$ |

| | | |
|---|---|---|
| $DRAINSF_j(X)$ | Drainage out of surface water compartment X, land unit j. | $m^3d^{-1}$ |
| DRFRC$_j$(X) | Variable drainage fraction of compartment X, land unit j. | $d^{-1}$ |
| DRWMAX | Maximum amount of drainage water in a compartment. | $m^3$ |
| DRWRT | Empirically determined drainage water retention factor. | $(\%m)^{-1}$ |
| $DUL_j(x)$ | Soil water content of root zone at drained upper limit, land unit j. | $m^3m^{-3}$ |
| $ET_j$ | Total actual evapotranspiration, land unit j. | mm $d^{-1}$ |
| $FC_j$ | Water content of soil root zone at field capacity, land unit j. | $m^3m^{-3}$ |
| $FLOWL_j$ | Length of flow path to stream, land unit j. | m |
| FLOWLMX | Maximum length of flow path to stream. | m |
| $FLUX_j$ | Downward flux of water into the soil root zone, land unit j. | mm $d^{-1}$ |
| $FR_{ST,x,d}$ | Desired equilibrium fraction of dam storage, dam x, day d. | [-] |
| $FRWC_j$ | Daily fraction of wet canopy evapotranspiration, land unit j. | [-] |
| $h_j$ | Average hydraulic head in land unit j. | m |
| $HOLD_j$ | Remaining water holding capacity of root zone, land unit j. | mm $d^{-1}$ |
| $IR_j$ | Applied irrigation, land unit j. | mm $d^{-1}$ |
| $K_j$ | Hydraulic conductivity, land unit j. | m $d^{-1}$ |
| $K_{AV,j}$ | Average hydraulic conductivity along the flow path, land unit j. | m $d^{-1}$ |
| $MET_j$ | Maximum evapotranspiration for actual land cover, land unit j. | mm $d^{-1}$ |
| $MX_{FL}$ | Maximum value of drainage correction factor for flow length. | [-] |
| $MX_{SW}$ | Maximum value of drainage correction factor for water content. | [-] |
| $P_{CUM,n,m}$ | Cumulative prob. of LU change from LU type n towards m. | [-] |
| $P_{G,j}$ | Gross precipitation, land unit j. | mm $d^{-1}$ |
| $P_{n,m}$ | Probability of LU change from LU type n towards m. | [-] |
| $P_{NORM,n,m}$ | Normalized probability of LU change from LU type n towards m. | [-] |
| $P_{N,j}$ | Net precipitation, land unit j | mm $d^{-1}$ |
| Q | Number of land units that form contributing area of a stream cell. | [-] |
| RD | Rooting depth, per land use type. | m |
| RELDRN | Relative daily drainage fraction. | $d^{-1}$ |
| $RET_j$ | Reference evapotranspiration, land unit j. | mm $d^{-1}$ |
| $RO_j$ | Surface runoff originating from land unit j. | mm $d^{-1}$ |
| $RT_{n,m,r}$ | Relative tendency of LU change from type n towards m, rule r. | [-] |
| $RT_{OV,n}$ | Overall relative tendencies of change from LU type n towards m. | [-] |

| | | |
|---|---|---|
| $RT_{SUM,n}$ | Sum of overall relative tendencies associated with LU type n. | [-] |
| RZDRF | Soil root zone drainage factor. | $d^{-1}$ |
| $S_j$ | Watershed storage parameter, land unit j. | mm |
| $SAT_j$ | Soil water content of root zone at saturation, land unit j. | $m^3m^{-3}$ |
| SEED | Random number generator "seed" value. | [-] |
| $SET_j$ | Water extraction from soil for evapotranspiration. | mm $d^{-1}$ |
| SFWRT | Surface water retention factor. | $d^{-1}$ |
| $SFW_j(X)$ | Water content in surface water compartment X, land unit j. | $m^3$ |
| $SLOPE_{AV,j}$ | Average slope along the flow path, land unit j. | % |
| $ST_x$ | Amount of water stored in stream cell x if it has a dam. | $m^3$ |
| $ST_{MX,x}$ | Storage capacity of a dam in stream cell x. | $m^3$ |
| $SW_j$ | Soil water content in the root zone, land unit j. | $m^3m^{-3}$ |
| $TOTDRS_x$ | Total drainage (lateral flow) into stream cell x. | $m^3d^{-1}$ |
| $TOTROS_x$ | Total surface runoff into stream cell x. | $m^3d^{-1}$ |
| $TRO_j(x)$ | Total surface runoff, land unit j. | mm $d^{-1}$ |
| $V_{x,x+1}$ | Stream flow from stream cell x to stream cell x+1. | $m^3d^{-1}$ |
| $V_{AGR,x}$ | Agricultural water use from stream cell or dam x. | $m^3d^{-1}$ |
| $V_{DOM,x}$ | Domestic water use from stream cell or dam x. | $m^3d^{-1}$ |
| $V_{REC,x}$ | Receiving flow of dam x (built in river). | $m^3d^{-1}$ |
| $V_{EXD,x}$ | Gross rate of flow into dam x (external to river). | $m^3d^{-1}$ |
| $V_{EXDMAX,x}$ | Maximum gross rate of flow into an external dam x. | $m^3d^{-1}$ |
| $V_{IND,x}$ | Industrial water use from stream cell or dam x. | $m^3d^{-1}$ |
| $V_{REM,x}$ | Remaining water after water use in dam x (built in river). | $m^3d^{-1}$ |
| $V_{RO,x}$ | Accumulated surface runoff into stream cell x. | $m^3d^{-1}$ |
| $V_{LF,x}$ | Accumulated lateral flow (drainage) into stream cell x. | $m^3d^{-1}$ |
| $V_{MIN,x}$ | Minimum required flow rate out of dam x (built in river). | $m^3d^{-1}$ |
| $V_{MAX,x}$ | Maximum allowed flow rate out of dam x (built in river). | $m^3d^{-1}$ |
| $V_{TOT,x}$ | Total, potentially extractable water supply in dam x (in river). | $m^3d^{-1}$ |
| $V_{OUT,x}$ | Specified, preliminary flow out of dam x (built in river). | $m^3d^{-1}$ |
| $V_{USE,x}$ | Total water use from stream cell or dam x. | $m^3d^{-1}$ |
| $WAT_j(X)$ | Water content in drainage water compartment X, land unit j. | $m^3$ |
| WATMAX | Maximum amount of water in a compartment. | $m^3$ |

| | | |
|---|---|---|
| $WP_j$ | Soil water content of root zone at wilting point, land unit j. | $m^3m^{-3}$ |
| x | Distance between the centers of two adjacent land units. | m |
| YRLUC | Annual probability of land use change. | $yr^{-1}$ |

APPENDIX D
SWBM INPUT DATA REQUIREMENTS

The Spatial Water Budget Model (SWBM) uses five different types of data. All data can be entered, or the associated file selected, through SWBM's GIS-based user-interface.

## Spatially Variable Parameters

Spatially variable parameters are properties of the soil and the landscape which may take different values for each land unit. Each parameter type is inputted as an ARC/INFO grid. All grids must have the same projection, spatial extent (entire catchment) and grid cell size. The ARC/INFO GRID (ESRI, 1994) or ArcView GIS (ESRI, 1997b) software can be used to create these grids in the correct format.

Table D-1. SWBM input data—spatially variable soil and landscape properties that may be different for each land unit. The data are inputted as ARC/INFO grids.

| Variable | Description | Unit |
|---|---|---|
| - | Digital elevation model | m |
| - | Land use/land cover type (integer values) | - |
| - | Stream network (*Null* value for grid cells that are no stream cell) | - |
| $K_{AV,j}$ | Average hydraulic conductivity along the flow path, land unit j | $m\ d^{-1}$ |
| $SLOPE_{AV,j}$ | Average slope along the flow path, land unit j | % |
| $DUL_j(x)$ | Soil water content of root zone at drained upper limit, land unit j | $m^3m^{-3}$ |
| $WP_j$ | Soil water content of root zone at wilting point, land unit j | $m^3m^{-3}$ |
| $SAT_j$ | Soil water content of root zone at saturation, land unit j | $m^3m^{-3}$ |

## Land Use/Land Cover Parameters

Land use/land cover parameters (Table D-2) depend on the land cover/land use type. These parameters are inputted in menus (only one value for each land use type) and saved in a single dBase IV file. This file has one record for each land use/land cover type. The user need not know the format of this file. Once the file has been created, changes in parameter values may be made directly in the file using any spreadsheet software that can read and write dBase formatted files, including ArcView GIS. At the start of each simulation run, SWBM automatically combines the data in the dBase file with the land use/land cover classification to create various temporary ARC/INFO grids.

Table D-2. SWBM input data—parameters that may be different for each land use/land cover type. The data are entered through the SWBM user-interface and saved in a dBase file.

| Variable | Description | Unit |
|---|---|---|
| - | Name of land use/land cover | - |
| $A_{ref}$ | Reference initial canopy interception (applies to CF =1) | mm |
| $B_{ref}$ | Reference canopy interception gradient (applies to CF=1) | [-] |
| $CN_{II}$ | SCS curve number for antecedent moisture conditions II | [-] |
| CFSW | Soil water content depletion fraction. | [-] |
| DLAYR | Thickness of soil root zone | m |
| CF | Crop coefficient, specified for each month. | [-] |

## Watershed-Scale Parameters

Watershed-scale (lumped) parameters (Table D-3) have the same value for all land units and are entered in a menu and saved in a single ASCII file. During the simulation, SWBM automatically creates an ARC/INFO grid, with the same value for each grid cell.

Table D-3. SWBM input data— parameters that have a uniform value for the entire watershed. The data are entered through the SWBM user-interface and saved in an ASCII file.

| Variable | Description | Unit |
|---|---|---|
| DRWRT | Empirically determined drainage water retention factor | $(\%m)^{-1}$ |
| FLOWLMX | Maximum length of flow path to stream | m |
| WATMAX | Maximum amount of water in a compartment | $m^3$ |
| $MX_{FL}$ | Maximum value of drainage correction factor for flow length | [-] |
| $MX_{SW}$ | Maximum value of drainage correction factor for water content | [-] |
| RZDRF | Soil root zone drainage factor | $d^{-1}$ |
| SFWRT | Surface water retention factor | $d^{-1}$ |

## Water Use Data

Water use data include the (x,y) location of water use points (which may be an existing dam) and the daily amounts of water extracted for domestic, agricultural and industrial uses (Table D-4). The locations are interactively selected by clicking on a stream map. Locations outside the stream network cannot be selected. Once selected, all water use rates can be specified in a series of menus. All data are stored in the same dBase file as the dam data.

Table D-4. SWBM input data—parameters that characterize water use from streams and dams. The data are entered through the SWBM user-interface and saved in a dBase file.

| Variable | Description | Unit |
|---|---|---|
| - | Coordinates of water extraction location *x*, selected from screen | - |
| $V_{DOM,x,d}$ | Domestic water use from stream cell or dam *x*, day *d* | $m^3d^{-1}$ |
| $V_{IND,x,d}$ | Industrial water use from stream cell or dam *x*, day *d* | $m^3d^{-1}$ |
| $V_{AGR,x,d}$ | Agricultural water use from stream cell or dam *x*, day *d* | $m^3d^{-1}$ |

## Characteristics and Operation of Dams

These parameters include the (x,y) location of dams, the dam storage capacity, the minimum required and maximum allowed flow rate at the location of the dam (Table D-5). The locations of dams are interactively selected by clicking on a map. Once selected, all parameters needed for the operation of the dam are specified in a series of menus and saved in a single dBase file (other than the file that contains the land use related data). Once the file has been created, changes in parameter values may be made directly in the file using any spreadsheet software that can read and write dBase formatted files, including ArcView GIS.

Table D-5. SWBM input data—parameters that characterize the size and operation of dams. The data are entered through the SWBM user-interface and saved in a dBase file.

| Variable | Description | Unit |
|---|---|---|
| - | Coordinates of dam *x*, selected from screen | - |
| $ST_{MX,x}$ | Storage capacity of dam *x* | $m^3$ |
| $V_{EXDMAX,x,d}$ | Maximum gross rate of flow into dam x, day *d* (external dam) | $m^3d^{-1}$ |
| $V_{MIN,x,d}$ | Minimum required flow rate at dam x, day *d* (dam in river; optional) | $m^3d^{-1}$ |
| $V_{MAX,x,d}$ | Maximum allowed flow rate at day x, day *d* (dam in river; optional) | $m^3d^{-1}$ |
| $V_{OUT,x,d}$ | Specified, preliminary flow out of dam *x,* day *d* (built in river) | $m^3d^{-1}$ |
| $FR_{ST,x,d}$ | Desired equilibrium fraction of dam storage capacity, dam *x*, day *d*. | [-] |

## Weather Data

Daily weather data from one or more weather stations in the region. All data from a station must be in a single ASCII file. Every data line contains six data entries: 4-digit year number, Julian day number, solar radiation, minimum temperature, maximum temperature and rainfall (Table D-6). Different weather stations must have different files.

Table D-6. SWBM input data—weather data. These must be stored in a single ASCII file.

| Variable | Description | Unit |
| --- | --- | --- |
| - | Minimum daily temperature | °C |
| - | Maximum daily temperature | °C |
| - | Solar radiation | MJ $m^{-2}d^{-1}$ |
| - | Daily rainfall | mm $d^{-1}$ |
| - | Elevation of the weather station | m |

# APPENDIX E
# OVEJAS RIVER FLOW DATA

Average monthly flow data of the Ovejas River were available for the years 1965 through 1988. These flow measurements were taken where the contributing area to the river is 61,500 ha (C. de Fraiture, 1996, personal communication); the entire Ovejas River watershed is larger. Tables E-1, E-2 and E-3 give the minimum, average and maximum monthly flow rates, respectively. Daily flow data of the Ovejas River were available only for 1974-1982 and 1984-1988 (1983 data were lost). For these years, Figures E-1 through E-14 graphically show the daily flow rates along with daily precipitation and the 24-year average flow rate. Notice that flow rate and precipitation are plotted against the same scale on the y-axis, but they have different units ($m^3s^{-1}$ and mm $d^{-1}$, respectively).

The precipitation data are averages of daily measurements from five weather stations in the Ovejas River watershed: Morales, El Amparo, Piendamo, Mondomo, and La Aguada. Monthly precipitation totals for the years 1974-1988 are given Table E-4.

Flow data of the Ovejas River were used to calibrate part of the SWBM for Cabuyal River. Specifically, they were used to calibrate the following hydrograph characteristics of simulated river flow: runoff peak flow rates, base flow retention rate, and minimum and maximum base flow during the year. Calibration took place by visual comparison of measured and simulated flow river flow rates.

Table E-1. Minimum flow rate of the Ovejas River, by month and year, in $m^3s^{-1}$, based on measurements taken at the point where the river has a catchment of 61,500 ha.

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1965 | 15.5 | 9.1 | 10.4 | 10.4 | 15.8 | 9.6 | 6.3 | 5.1 | 4.8 | 3.4 | 10.4 | 20.5 | 3.4 |
| 1966 | 11.5 | 7.6 | 7.3 | 6.7 | 9.7 | 11.9 | 7.0 | 5.3 | 3.4 | 5.2 | 6.8 | 28.2 | 3.4 |
| 1967 | 13.0 | 12.6 | 15.8 | 14.7 | 13.0 | 12.8 | 7.9 | 5.7 | 3.8 | 4.7 | 9.2 | 12.2 | 3.8 |
| 1968 | 10.1 | 15.9 | 13.5 | 11.9 | 12.8 | 11.9 | 7.6 | 5.7 | 4.2 | 4.9 | 10.3 | 16.2 | 4.2 |
| 1969 | 12.5 | 15.2 | 11.9 | 13.5 | 19.6 | 13.8 | 7.6 | 5.2 | 2.7 | 6.1 | 17.6 | 17.6 | 2.7 |
| 1970 | 13.4 | 17.6 | 16.8 | 15.3 | 13.4 | 12.3 | 8.5 | 5.7 | 4.2 | 7.3 | 15.6 | 22.2 | 4.2 |
| 1971 | 20.8 | 24.5 | 27.9 | 25.9 | 24.1 | 14.2 | 9.7 | 7.5 | 6.1 | 6.5 | 14.2 | 13.9 | 6.1 |
| 1972 | 19.2 | 22.7 | 19.2 | 20.0 | 20.0 | 11.0 | 8.1 | 6.6 | 5.3 | 5.3 | 7.8 | 13.1 | 5.3 |
| 1973 | 8.7 | 6.8 | 6.8 | 9.0 | 13.8 | 13.1 | 9.3 | 9.6 | 13.4 | 15.8 | 23.7 | 33.4 | 6.8 |
| 1974 | 26.5 | 36.7 | 32.8 | 22.3 | 18.3 | 13.8 | 9.9 | 7.5 | 6.8 | 9.9 | 16.6 | 17.9 | 6.8 |
| 1975 | 14.2 | 12.9 | 22.9 | 16.4 | 17.2 | 12.1 | 13.8 | 9.8 | 8.3 | 8.3 | 27.5 | 35.8 | 8.3 |
| 1976 | 20.0 | 20.5 | 21.9 | 21.9 | 19.6 | 10.9 | 6.6 | 4.4 | 3.3 | 4.1 | 11.7 | 12.5 | 3.3 |
| 1977 | 9.0 | 7.6 | 5.0 | 6.2 | 12.9 | 10.8 | 7.1 | 5.9 | 5.4 | 7.8 | 12.1 | 9.6 | 5.0 |
| 1978 | 12.8 | 9.0 | 8.4 | 10.5 | 13.5 | 9.9 | 7.8 | 7.1 | 5.4 | 5.4 | 6.6 | 11.1 | 5.4 |
| 1979 | 12.8 | 10.5 | 10.2 | 14.2 | 14.2 | 16.5 | 8.4 | 7.3 | 10.8 | 10.2 | 21.5 | 13.4 | 7.3 |
| 1980 | 9.9 | 18.0 | 14.9 | 12.1 | 10.8 | 8.7 | 6.3 | 5.6 | 5.6 | 6.1 | 6.8 | 8.1 | 5.6 |
| 1981 | 9.9 | 8.1 | 10.2 | 13.5 | 24.5 | 15.7 | 10.2 | 8.7 | 6.6 | 6.6 | 9.3 | 15.3 | 6.6 |
| 1982 | 16.1 | 19.6 | 29.1 | 28.1 | 27.5 | 14.5 | 9.4 | 6.6 | 5.9 | 7.1 | 10.8 | 13.8 | 5.9 |
| 1983 | 13.1 | 12.5 | 12.8 | 21.1 | 20.4 | 12.1 | 9.0 | 6.8 | 5.4 | 4.9 | 6.6 | 8.7 | 4.9 |
| 1984 | 18.4 | 18.4 | 17.2 | 20.0 | 28.6 | 17.2 | 11.8 | 8.4 | 8.1 | 11.1 | 21.1 | 19.6 | 8.1 |
| 1985 | 19.6 | 14.9 | 13.5 | 14.9 | 18.4 | 12.7 | 8.7 | 6.5 | 6.2 | 6.8 | 13.0 | 14.2 | 6.2 |
| 1986 | 16.3 | 20.7 | 23.5 | 12.4 | 11.2 | 11.9 | 7.4 | 6.8 | 4.5 | 8.1 | 15.9 | 10.8 | 4.5 |
| 1987 | 10.5 | 7.5 | 7.5 | 7.8 | 9.8 | 8.4 | 5.3 | 4.8 | 4.3 | 11.9 | 13.9 | 14.7 | 4.3 |
| 1988 | 9.1 | 6.8 | 6.8 | 6.8 | 10.3 | 11.6 | 11.6 | 9.9 | 7.6 | 7.6 | 18.7 | 29.1 | 6.8 |
| Mean | 14.3 | 14.8 | 15.3 | 14.8 | 16.6 | 12.4 | 8.6 | 6.8 | 5.9 | 7.3 | 13.7 | 17.2 | 5.4 |

Source: de Fraiture et al. (1997).

Table E-2. Average flow rate of the Ovejas River, by month and year, in $m^3s^{-1}$, based on measurements taken at the point where the river has a catchment of 61,500 ha

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1965 | 21.7 | 14.3 | 12.3 | 18.7 | 21.6 | 12.4 | 9.1 | 7.3 | 7.3 | 13.3 | 26.6 | 34.5 | 16.6 |
| 1966 | 17.4 | 11.8 | 10.9 | 12.4 | 17.0 | 14.8 | 10.0 | 7.0 | 5.4 | 9.4 | 22.9 | 52.5 | 16.0 |
| 1967 | 20.1 | 19.4 | 24.0 | 19.4 | 19.8 | 17.9 | 10.4 | 7.0 | 5.8 | 8.3 | 21.9 | 16.7 | 15.9 |
| 1968 | 13.7 | 23.2 | 17.7 | 19.7 | 16.3 | 16.8 | 9.7 | 7.0 | 6.6 | 13.1 | 23.5 | 26.8 | 16.2 |
| 1969 | 16.8 | 19.1 | 14.9 | 35.2 | 35.4 | 18.5 | 10.1 | 7.1 | 6.0 | 16.6 | 29.2 | 25.6 | 19.5 |
| 1970 | 17.2 | 28.5 | 28.4 | 18.5 | 22.3 | 17.4 | 10.2 | 6.9 | 6.2 | 12.0 | 43.1 | 27.8 | 19.9 |
| 1971 | 34.2 | 36.7 | 41.8 | 41.7 | 30.1 | 18.3 | 11.5 | 9.1 | 8.1 | 13.1 | 20.5 | 22.2 | 23.9 |
| 1972 | 30.5 | 30.4 | 26.8 | 26.9 | 26.3 | 15.4 | 9.9 | 7.6 | 6.3 | 7.5 | 16.5 | 21.1 | 18.8 |
| 1973 | 11.5 | 8.5 | 9.6 | 17.7 | 18.9 | 15.9 | 11.3 | 13.7 | 18.5 | 23.0 | 40.2 | 45.9 | 19.6 |
| 1974 | 37.9 | 54.1 | 56.7 | 30.6 | 27.5 | 16.2 | 11.5 | 8.5 | 9.0 | 18.1 | 36.0 | 27.6 | 27.8 |
| 1975 | 23.3 | 36.8 | 34.3 | 22.7 | 25.5 | 15.9 | 20.2 | 12.2 | 10.9 | 19.7 | 42.5 | 60.0 | 27.0 |
| 1976 | 32.8 | 33.5 | 26.6 | 29.8 | 24.3 | 14.9 | 8.8 | 6.2 | 4.4 | 13.6 | 17.8 | 17.3 | 19.2 |
| 1977 | 11.0 | 8.9 | 8.7 | 14.8 | 21.1 | 13.5 | 9.5 | 7.1 | 6.8 | 11.7 | 18.1 | 11.7 | 11.9 |
| 1978 | 20.7 | 10.9 | 9.7 | 16.8 | 18.4 | 12.3 | 9.7 | 8.6 | 7.2 | 7.5 | 10.1 | 18.9 | 12.6 |
| 1979 | 16.2 | 12.7 | 24.5 | 20.5 | 27.1 | 27.3 | 11.4 | 10.9 | 15.8 | 21.3 | 30.4 | 19.3 | 19.8 |
| 1980 | 17.0 | 31.5 | 23.2 | 15.0 | 14.6 | 11.2 | 8.3 | 6.9 | 7.0 | 9.9 | 9.3 | 13.2 | 13.9 |
| 1981 | 12.8 | 14.1 | 15.8 | 20.8 | 31.8 | 21.8 | 14.9 | 9.9 | 7.8 | 8.8 | 19.2 | 20.2 | 16.5 |
| 1982 | 35.7 | 29.6 | 38.1 | 36.1 | 34.6 | 21.4 | 12.0 | 8.4 | 7.9 | 12.6 | 16.8 | 21.7 | 22.9 |
| 1983 | 17.9 | 22.0 | 22.4 | 39.5 | 26.8 | 17.2 | 7.7 | 6.3 | 7.0 | 9.6 | 16.6 | 17.0 | 17.5 |
| 1984 | 26.2 | 26.5 | 22.1 | 26.4 | 42.0 | 26.0 | 15.8 | 10.7 | 12.0 | 21.7 | 36.0 | 28.1 | 24.5 |
| 1985 | 36.0 | 23.6 | 16.4 | 20.9 | 25.4 | 18.3 | 10.9 | 9.0 | 8.3 | 14.0 | 27.4 | 21.3 | 19.3 |
| 1986 | 26.8 | 32.8 | 37.0 | 23.4 | 19.8 | 15.2 | 10.2 | 7.7 | 7.2 | 17.4 | 22.6 | 17.4 | 19.8 |
| 1987 | 13.3 | 9.9 | 9.6 | 10.7 | 17.6 | 10.4 | 8.0 | 6.5 | 6.7 | 21.4 | 25.2 | 25.5 | 13.7 |
| 1988 | 12.3 | 9.1 | 8.9 | 11.8 | 14.9 | 16.9 | 17.7 | 11.4 | 9.5 | 15.2 | 41.1 | 45.1 | 17.8 |
| Mean | 21.8 | 22.8 | 22.5 | 22.9 | 24.1 | 16.9 | 11.2 | 8.5 | 8.2 | 14.1 | 25.6 | 26.6 | 18.8 |

Source: de Fraiture et al. (1997).

Table E-3. Maximum flow rate of the Ovejas River, by month and year, in $m^3s^{-1}$, based on measurements taken at the point where the river has a catchment of 61,500 ha

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1965 | 50.8 | 20.9 | 19.4 | 39.1 | 36.2 | 15.8 | 12.3 | 13.5 | 25.6 | 99.3 | 95.6 | 70.8 | 99.3 |
| 1966 | 41.2 | 26.0 | 40.0 | 33.9 | 51.3 | 57.0 | 20.0 | 19.0 | 13.8 | 21.1 | 63.0 | 122.2 | 122.2 |
| 1967 | 31.4 | 46.6 | 108.1 | 33.2 | 49.2 | 51.2 | 15.9 | 12.5 | 14.1 | 33.8 | 45.7 | 29.8 | 108.1 |
| 1968 | 42.9 | 67.7 | 35.3 | 51.2 | 27.1 | 46.3 | 31.3 | 10.3 | 15.2 | 66.2 | 83.5 | 81.9 | 83.5 |
| 1969 | 60.2 | 34.8 | 29.4 | 145.2 | 95.2 | 40.3 | 13.4 | 10.7 | 25.3 | 35.5 | 50.0 | 44.7 | 145.2 |
| 1970 | 32.0 | 67.5 | 56.6 | 68.9 | 64.9 | 40.9 | 13.8 | 12.7 | 15.3 | 25.3 | 100.1 | 62.2 | 100.1 |
| 1971 | 98.9 | 104.9 | 144.5 | 106.6 | 67.6 | 31.5 | 15.4 | 17.4 | 11.3 | 26.9 | 32.0 | 106.6 | 144.5 |
| 1972 | 99.6 | 91.1 | 134.0 | 44.3 | 33.9 | 24.1 | 11.3 | 15.4 | 26.5 | 31.7 | 43.7 | 58.6 | 134.0 |
| 1973 | 16.2 | 22.2 | 60.0 | 47.4 | 51.9 | 67.0 | 32.8 | 101.0 | 49.9 | 55.8 | 134.0 | 129.2 | 134.0 |
| 1974 | 89.5 | 91.9 | 251.9 | 41.9 | 37.2 | 18.3 | 13.8 | 9.6 | 28.1 | 119.2 | 140.9 | 57.9 | 251.9 |
| 1975 | 101.9 | 104.8 | 63.0 | 72.9 | 38.1 | 21.0 | 56.2 | 21.0 | 34.7 | 118.7 | 118.0 | 135.9 | 135.9 |
| 1976 | 60.9 | 135.9 | 37.5 | 87.5 | 31.9 | 20.5 | 11.3 | 7.3 | 8.3 | 42.3 | 36.4 | 49.7 | 135.9 |
| 1977 | 15.1 | 14.6 | 43.5 | 64.6 | 63.0 | 46.0 | 26.5 | 11.5 | 20.4 | 23.5 | 32.4 | 18.0 | 64.6 |
| 1978 | 42.9 | 19.6 | 17.2 | 90.5 | 46.0 | 22.0 | 12.1 | 9.3 | 9.6 | 22.9 | 29.7 | 44.7 | 90.5 |
| 1979 | 33.5 | 17.2 | 56.9 | 50.3 | 99.1 | 83.0 | 17.2 | 28.1 | 22.0 | 68.3 | 41.1 | 30.7 | 99.1 |
| 1980 | 38.7 | 101.4 | 31.8 | 35.8 | 99.0 | 20.8 | 12.1 | 14.2 | 32.4 | 57.5 | 17.2 | 40.5 | 101.4 |
| 1981 | 20.8 | 32.4 | 24.0 | 67.8 | 57.5 | 65.9 | 32.4 | 15.3 | 9.6 | 17.2 | 44.7 | 39.3 | 67.8 |
| 1982 | 103.7 | 92.2 | 73.9 | 58.9 | 67.8 | 33.5 | 16.1 | 10.8 | 24.0 | 44.1 | 33.0 | 36.4 | 103.7 |
| 1983 | 26.0 | 106.4 | 86.8 | 87.5 | 65.9 | 23.5 | 13.5 | 9.0 | 7.3 | 19.2 | 21.5 | 54.3 | 106.4 |
| 1984 | 104.3 | 53.6 | 51.6 | 99.6 | 129.7 | 47.2 | 46.0 | 42.3 | 40.5 | 99.1 | 96.5 | 51.0 | 129.7 |
| 1985 | 86.8 | 39.9 | 59.6 | 48.5 | 62.3 | 57.7 | 24.0 | 22.6 | 25.0 | 58.3 | 85.3 | 70.7 | 86.8 |
| 1986 | 73.4 | 125.5 | 68.7 | 57.7 | 59.4 | 30.1 | 13.8 | 18.4 | 27.0 | 54.9 | 49.3 | 30.6 | 125.5 |
| 1987 | 36.2 | 21.2 | 31.2 | 35.6 | 64.1 | 12.3 | 19.8 | 17.6 | 68.0 | 68.0 | 112.5 | 70.0 | 112.5 |
| 1988 | 22.9 | 27.5 | 38.2 | 52.1 | 65.9 | 41.9 | 40.1 | 19.1 | 34.7 | 46.9 | 187.0 | 214.6 | 214.6 |
| Mean | 55.4 | 61.1 | 65.1 | 63.4 | 61.0 | 38.2 | 21.7 | 19.5 | 24.5 | 52.3 | 70.5 | 68.8 | 120.7 |

Source: de Fraiture et al. (1997).

Table E-4. Monthly and annual rainfall (mm) in the Ovejas River watershed, 1974-1988, aggregated from daily measurements at the Morales, El Amparo, Piendamo, Mondomo, and La Aguada weather stations.

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1974 | 284 | 375 | 384 | 248 | 188 | 133 | 128 | 43 | 224 | 284 | 390 | 141 | 2823 |
| 1975 | 110 | 361 | 181 | 188 | 284 | 131 | 218 | 154 | 133 | 242 | 373 | 384 | 2758 |
| 1976 | 121 | 205 | 200 | 195 | 148 | 46 | 8 | 56 | 80 | 270 | 196 | 170 | 1695 |
| 1977 | 76 | 94 | 170 | 288 | 165 | 93 | 34 | 55 | 116 | 271 | 230 | 167 | 1758 |
| 1978 | 148 | 62 | 240 | 246 | 180 | 72 | 82 | 38 | 126 | 164 | 211 | 360 | 1931 |
| 1979 | 198 | 126 | 314 | 302 | 240 | 86 | 49 | 242 | 163 | 262 | 265 | 107 | 2355 |
| 1980 | 182 | 250 | 89 | 160 | 141 | 78 | 27 | 65 | 87 | 238 | 145 | 166 | 1628 |
| 1981 | 88 | 247 | 267 | 273 | 319 | 133 | 99 | 95 | 47 | 243 | 355 | 186 | 2352 |
| 1982 | 316 | 233 | 358 | 347 | 226 | 57 | 48 | 4 | 166 | 337 | 275 | 233 | 2601 |
| 1983 | 146 | 129 | 274 | 366 | 230 | 48 | 37 | 44 | 37 | 288 | 188 | 275 | 2063 |
| 1984 | 347 | 291 | 253 | 228 | 336 | 133 | 121 | 138 | 231 | 388 | 260 | 174 | 2899 |
| 1985 | 338 | 88 | 203 | 194 | 160 | 61 | 63 | 160 | 130 | 210 | 251 | 146 | 2003 |
| 1986 | 254 | 294 | 184 | 232 | 157 | 88 | 9 | 58 | 167 | 390 | 193 | 102 | 2127 |
| 1987 | 156 | 129 | 190 | 180 | 245 | 55 | 90 | 47 | 103 | 409 | 207 | 92 | 1903 |
| 1988 | 106 | 134 | 70 | 301 | 170 | 156 | 114 | 108 | 137 | 249 | 479 | 258 | 2281 |
| Mean | 191 | 201 | 225 | 250 | 213 | 91 | 75 | 87 | 130 | 283 | 268 | 197 | 2211 |

Source: de Fraiture et al. (1997).

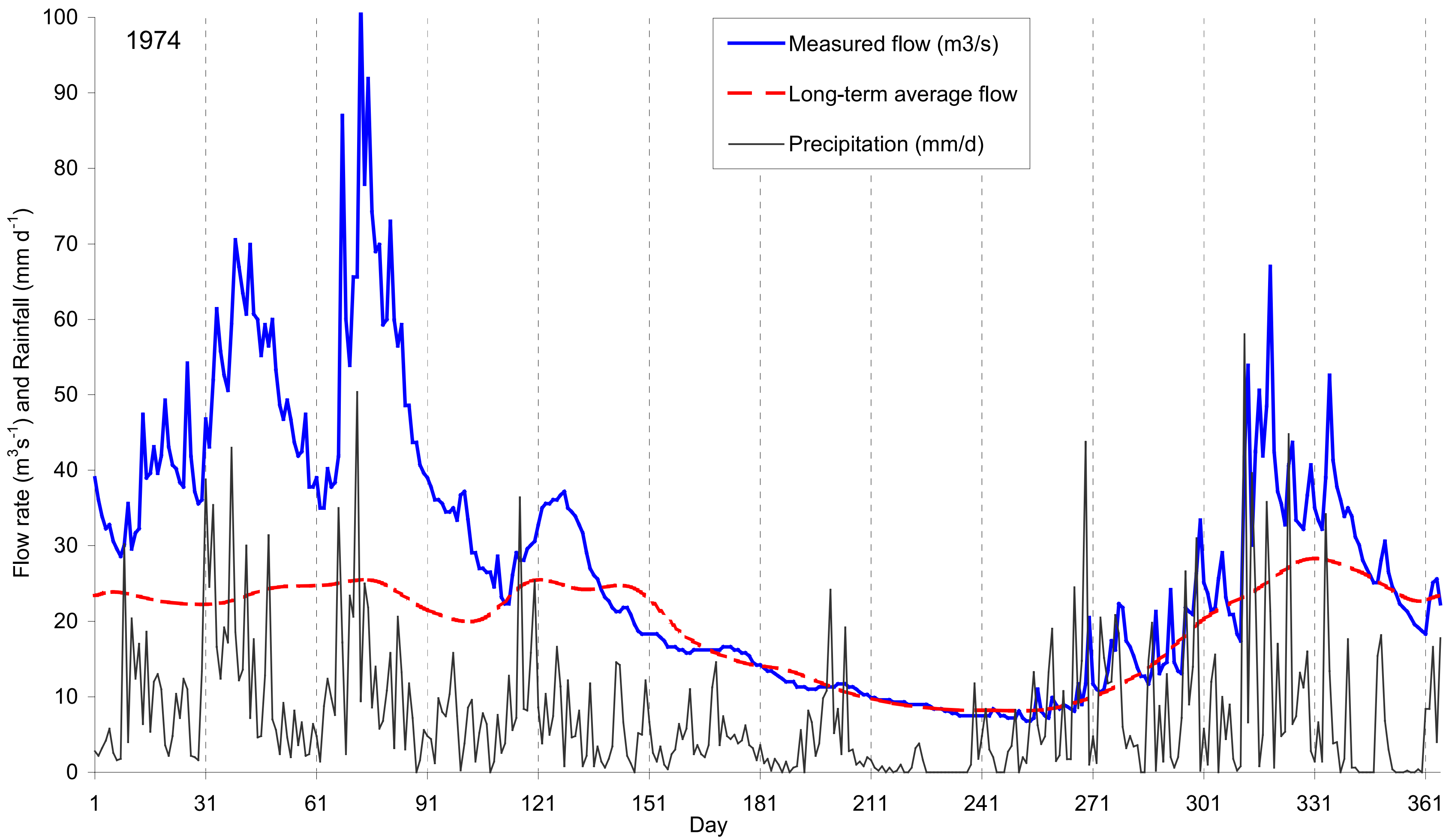



Figure E-1. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1974. Annual precipitation was 2,823 mm. Average river flow was 27.8 $m^3s^{-1}$ (corresponds to 1,426 mm $yr^{-1}$).

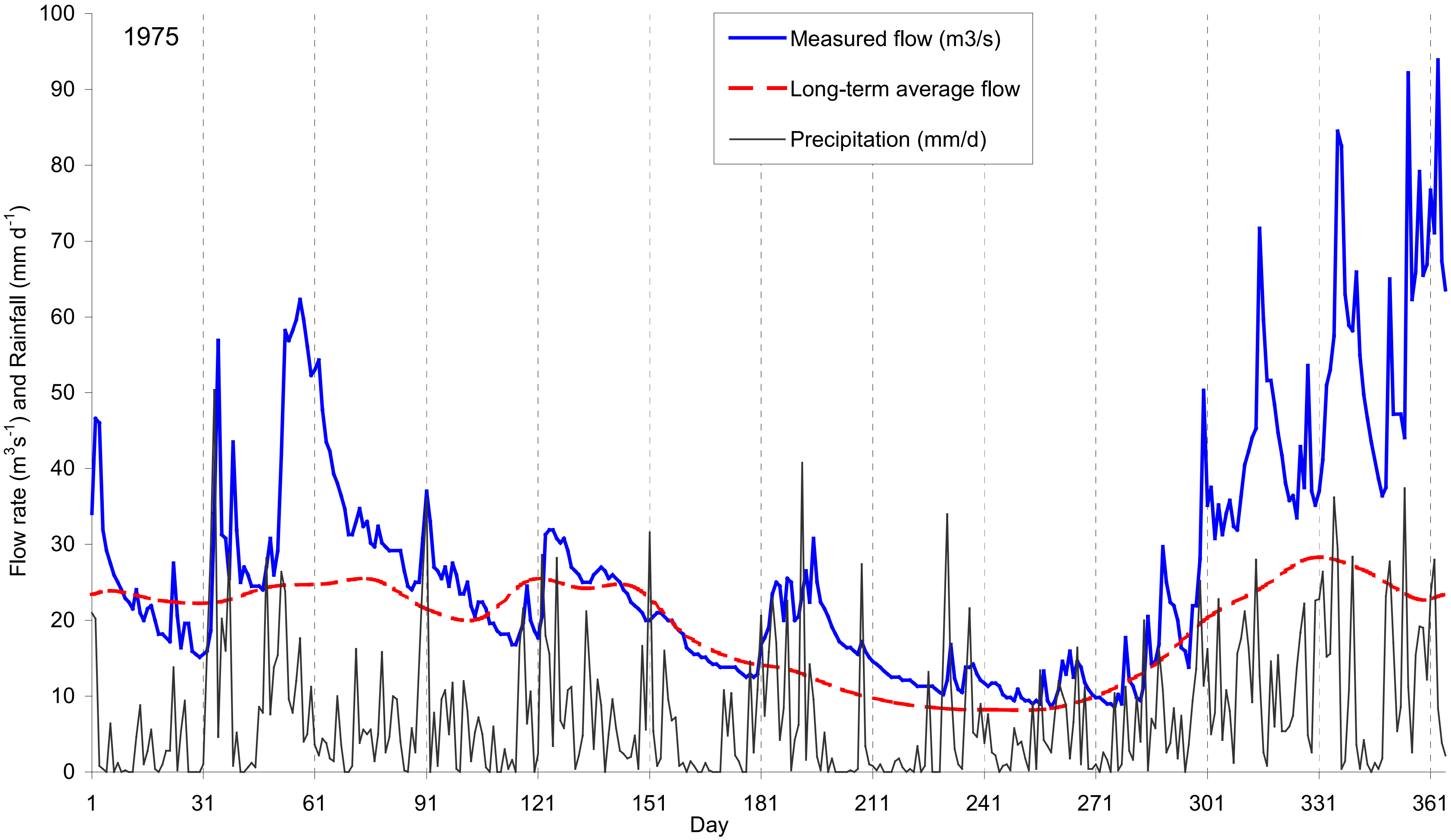



Figure E-2. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1975. Annual precipitation was 2,758 mm. Average river flow was 27.0 $m^3s^{-1}$ (corresponds to 1,385 mm $yr^{-1}$).

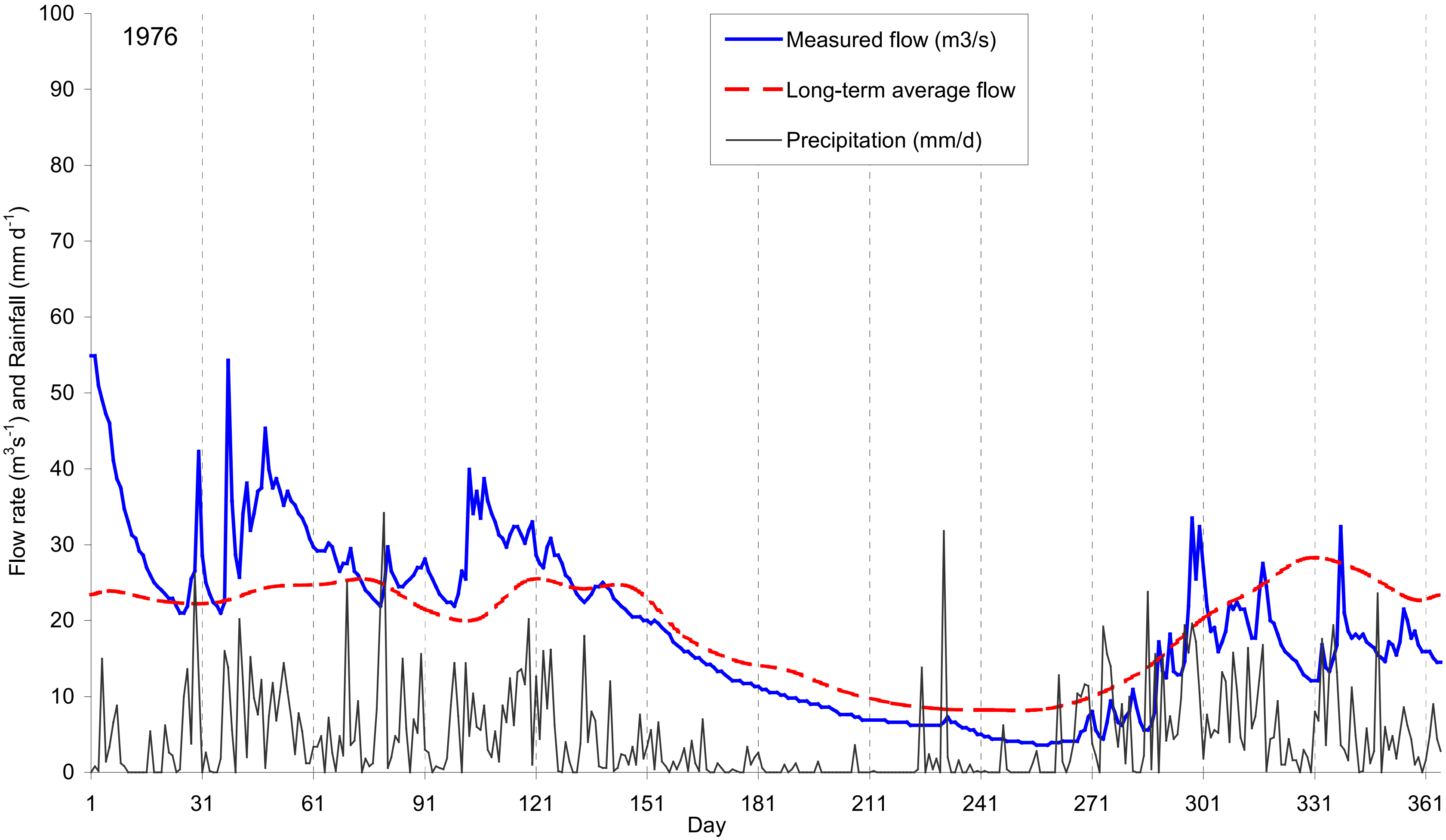



Figure E-3. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1976. Annual precipitation was 1,695 mm. Average river flow was 19.2 $m^3s^{-1}$ (corresponds to 983 mm $yr^{-1}$).

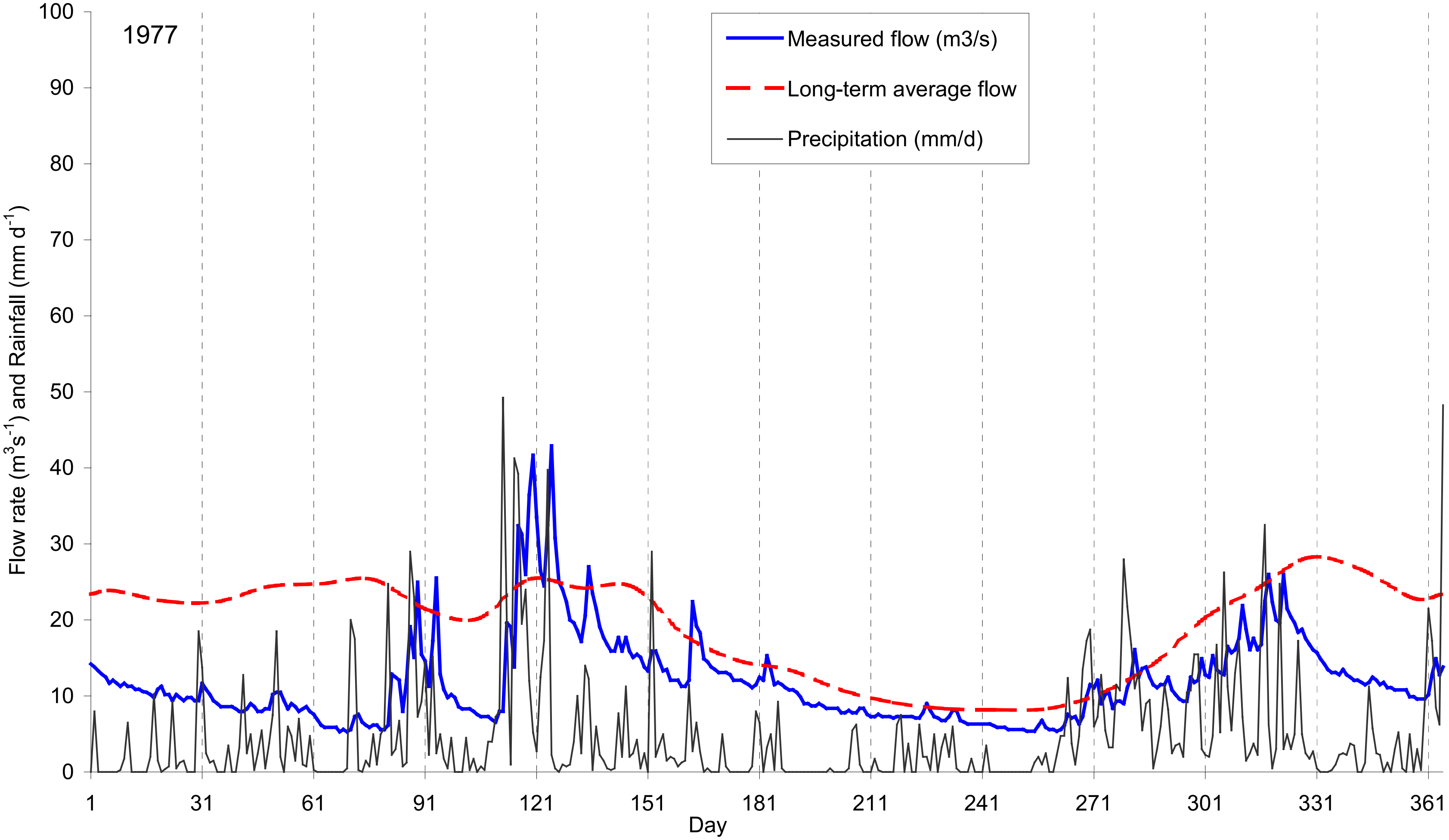



Figure E-4. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1977. Annual precipitation was 1,758 mm. Average river flow was 11.9 $m^3s^{-1}$ (corresponds to 611 mm $yr^{-1}$).

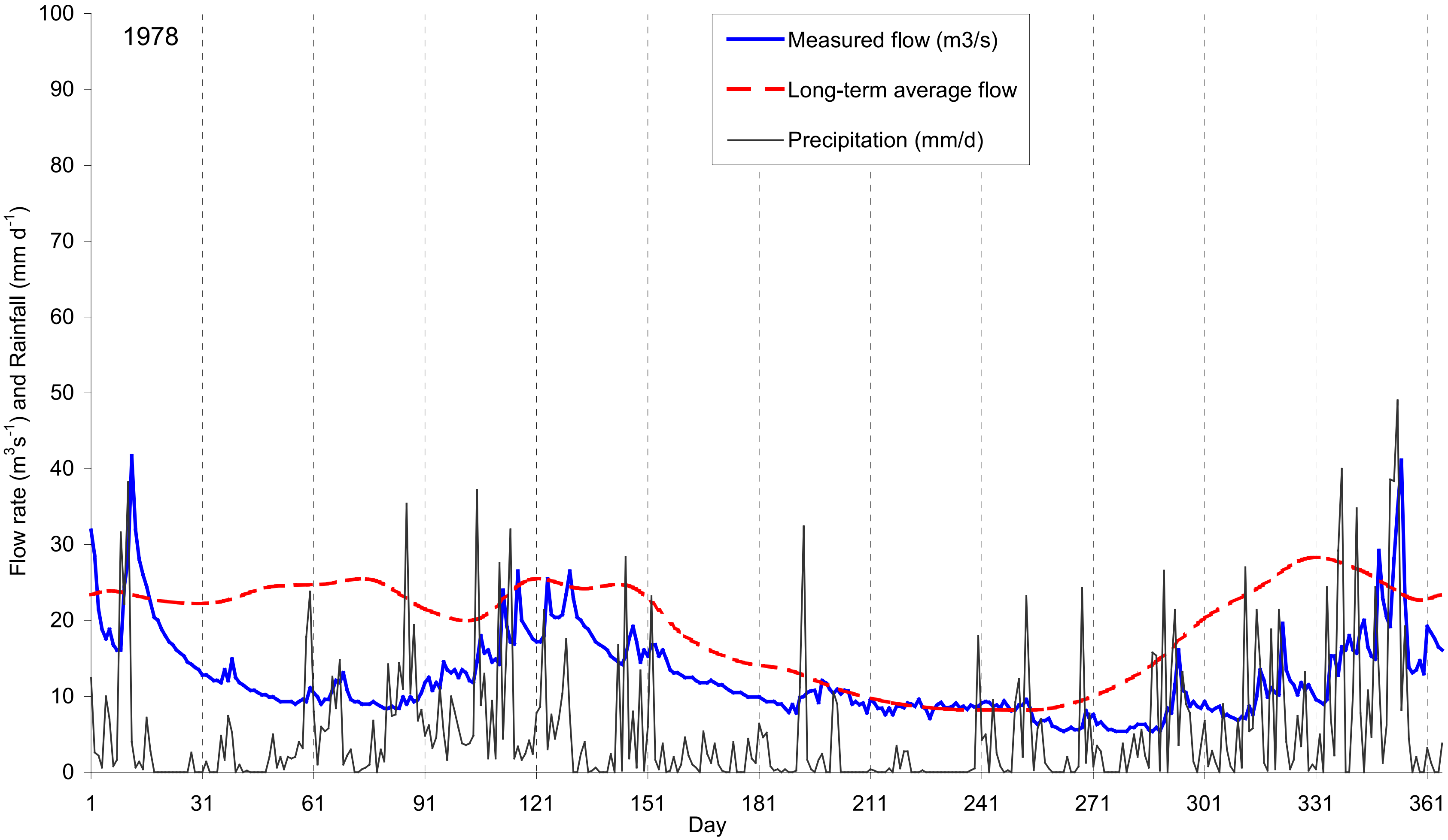



Figure E-5. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1978. Annual precipitation was 1,931 mm. Average river flow was 12.6 $m^3s^{-1}$ (corresponds to 644 mm $yr^{-1}$).

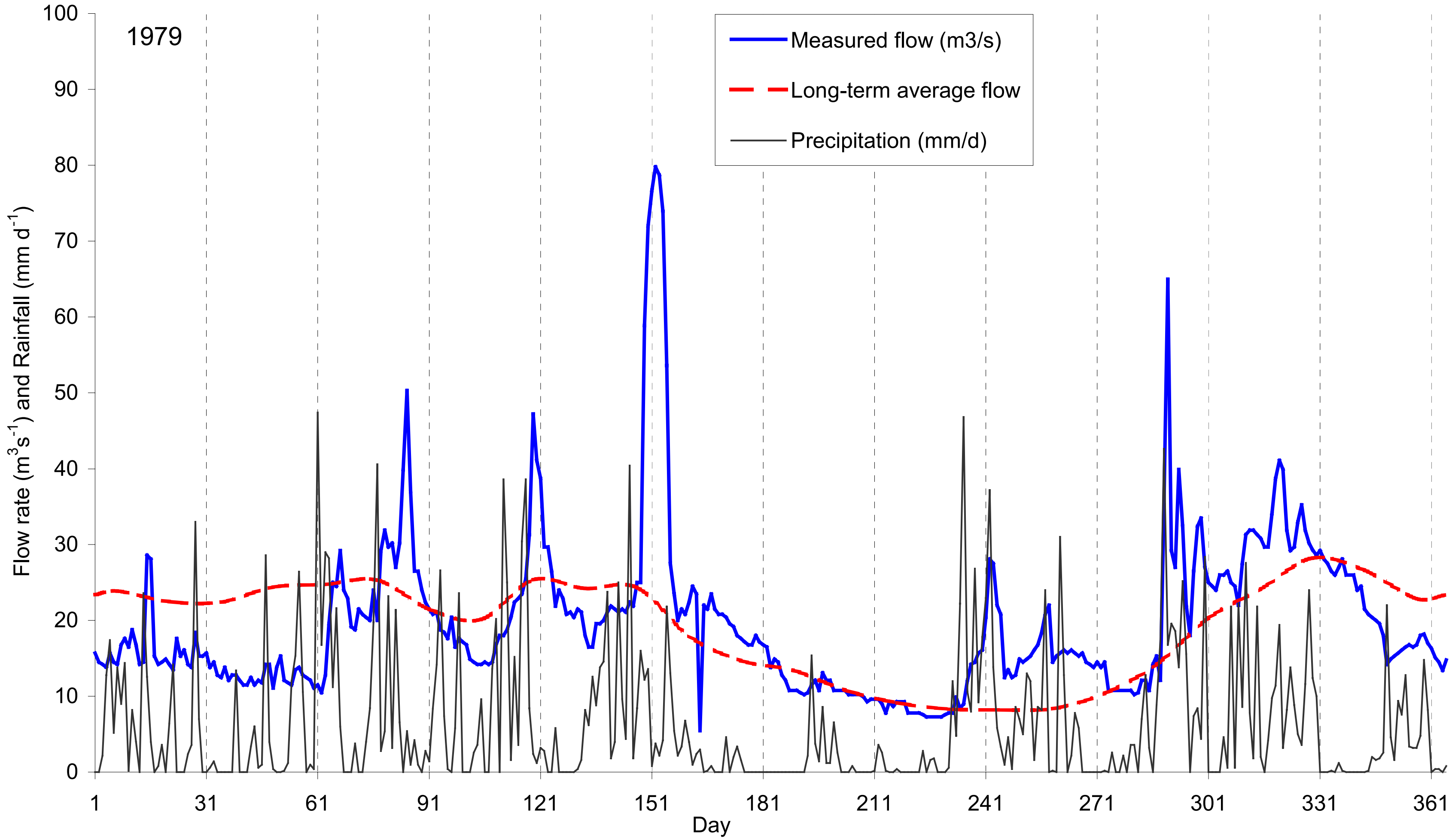



Figure E-6. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1979. Annual precipitation was 2,355 mm. Average river flow was 19.8 $m^3s^{-1}$ (corresponds to 1,014 mm $yr^{-1}$).

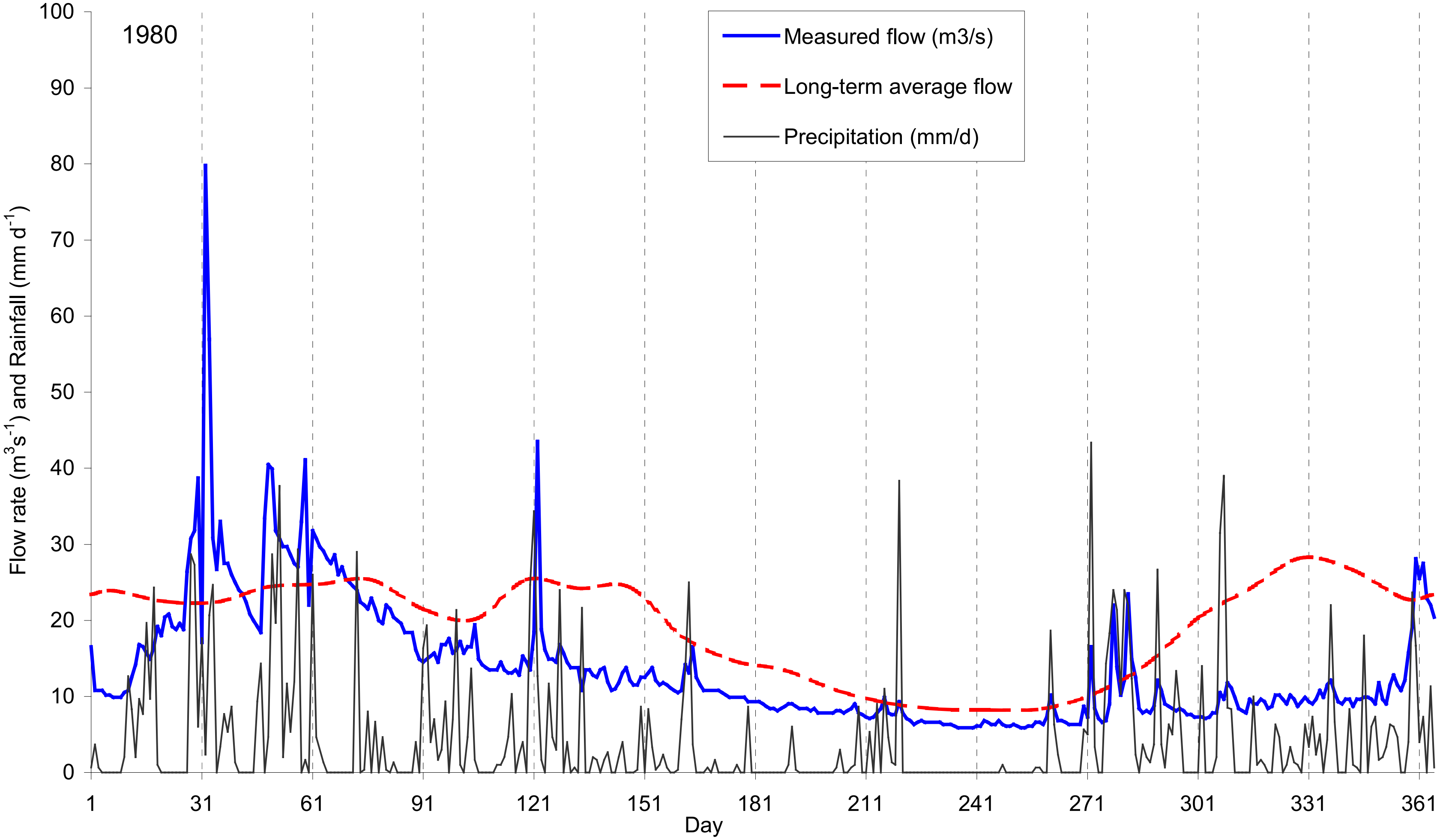



Figure E-7. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1980. Annual precipitation was 1,628 mm. Average river flow was 13.9 $m^3s^{-1}$ (corresponds to 714 mm $yr^{-1}$).

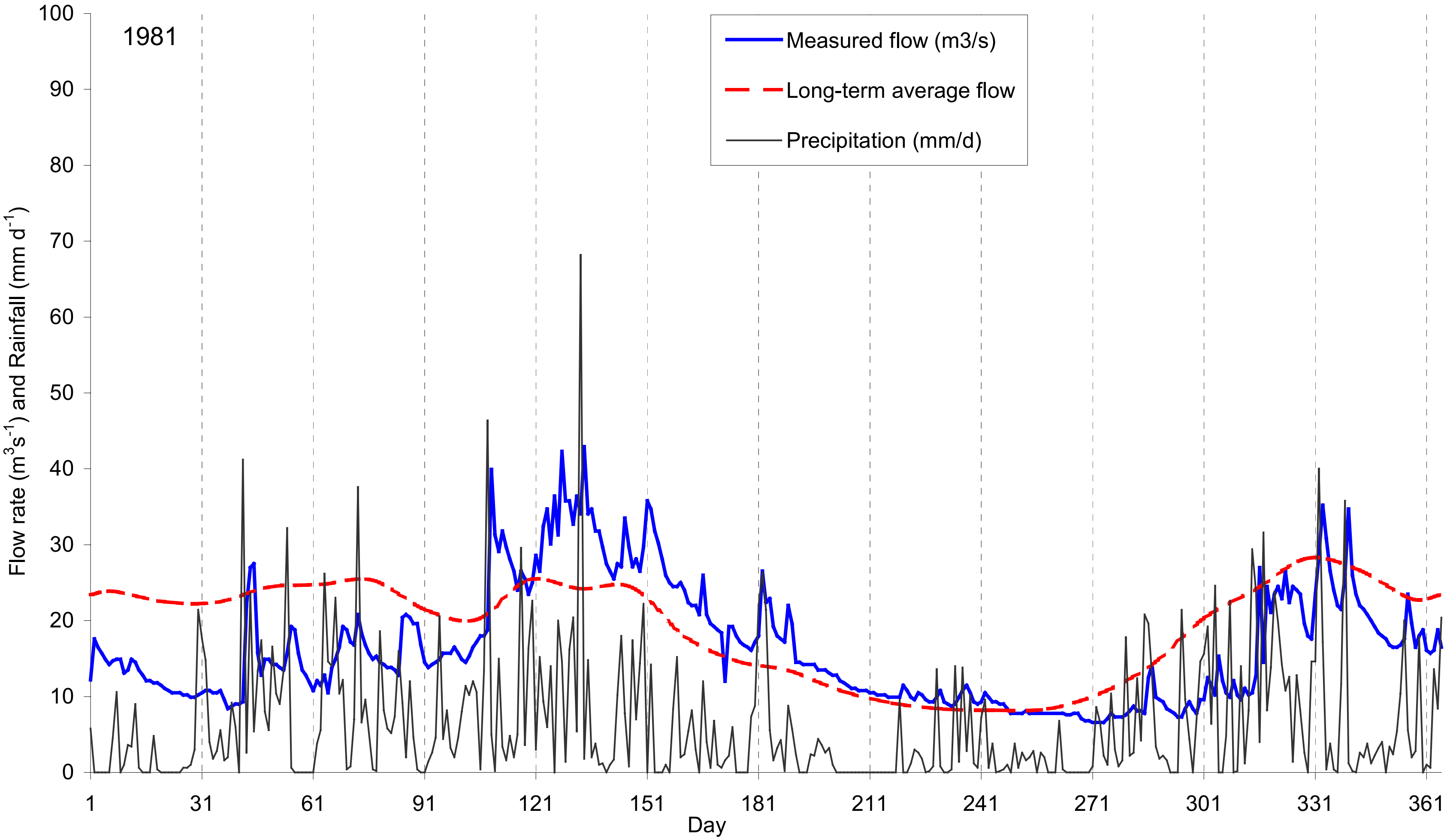



Figure E-8. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1981. Annual precipitation was 2,352 mm. Average river flow was 16.5 $m^3s^{-1}$ (corresponds to 846 mm $yr^{-1}$).

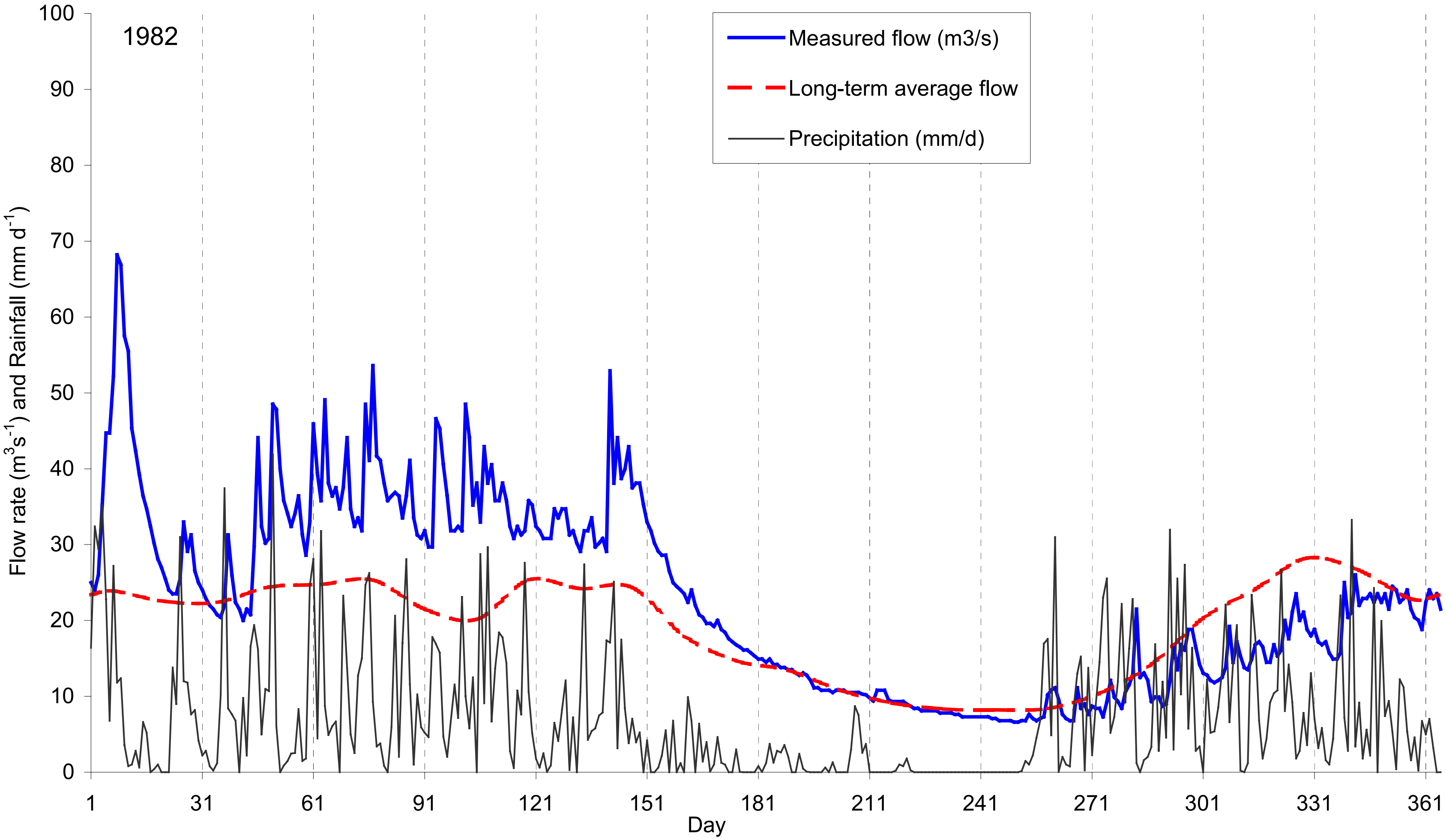



Figure E-9. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1982. Annual precipitation was 2,601 mm. Average river flow was 22.9 $m^3s^{-1}$ (corresponds to 1,174 mm $yr^{-1}$).

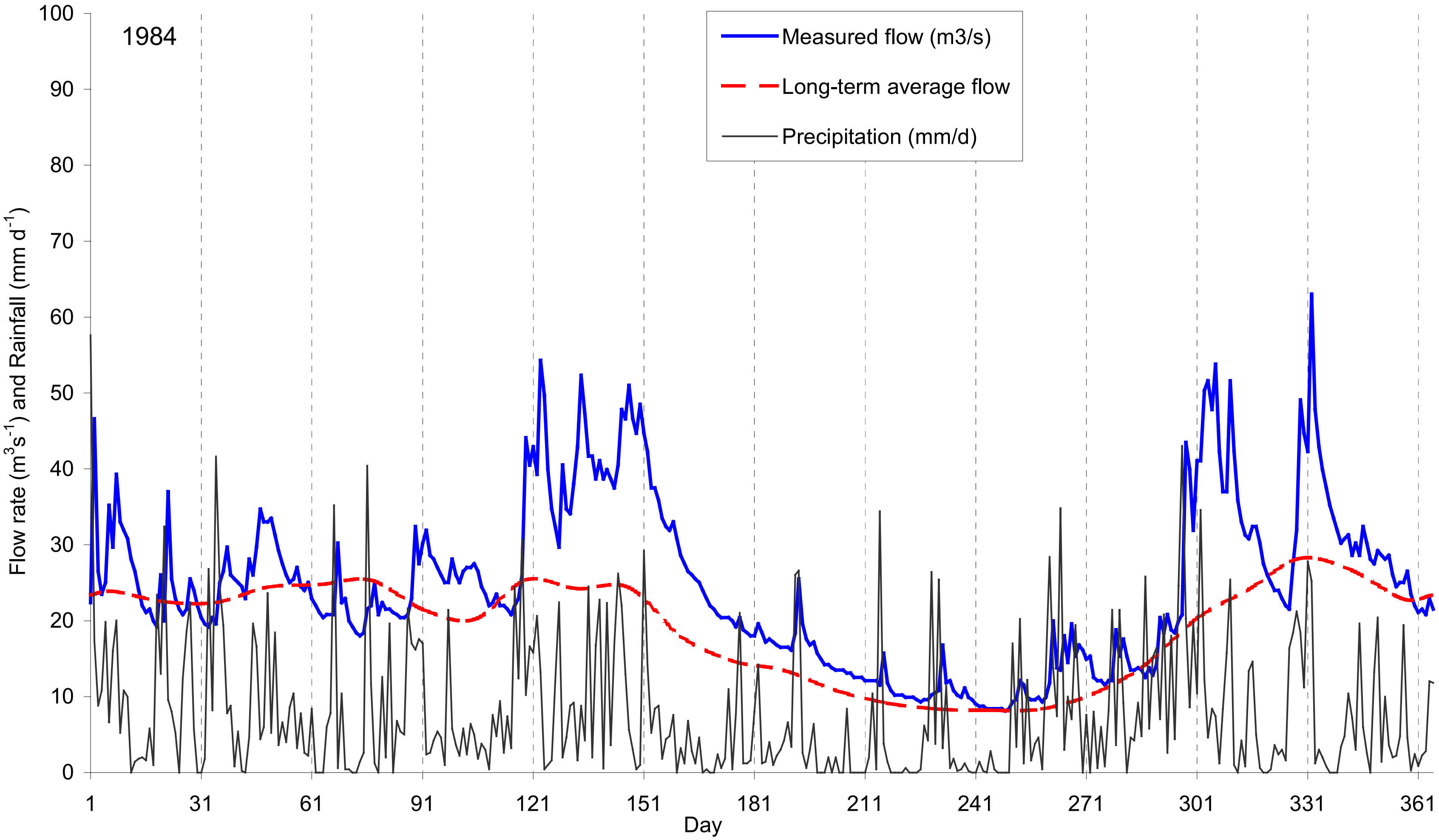



Figure E-10. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1984. Annual precipitation was 2,899 mm. Average river flow was 24.5 $m^3s^{-1}$ (corresponds to 1,254 mm $yr^{-1}$).

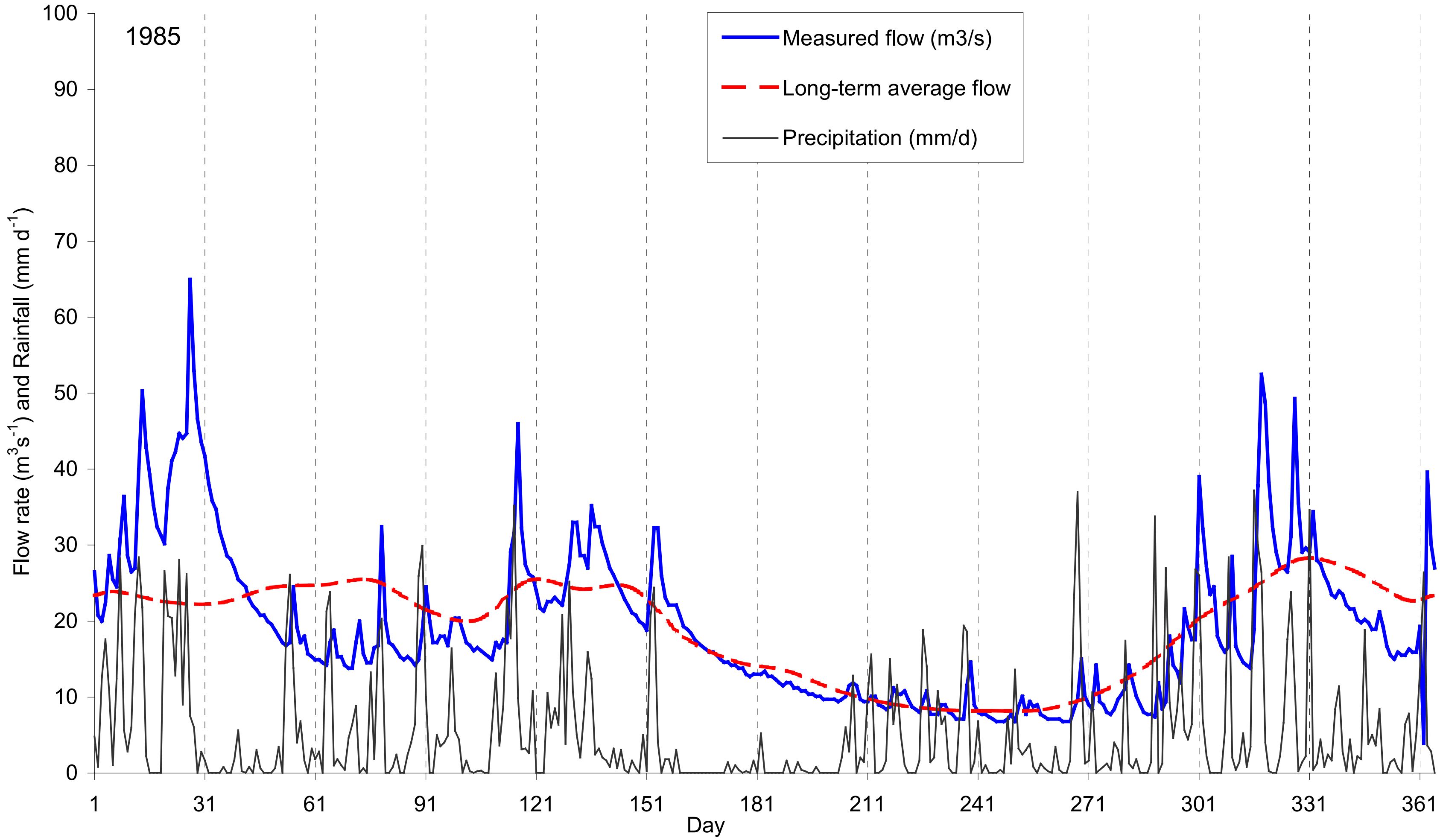



Figure E-11. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1985. Annual precipitation was 2,003 mm. Average river flow was 19.3 $m^3s^{-1}$ (corresponds to 989 mm $yr^{-1}$).

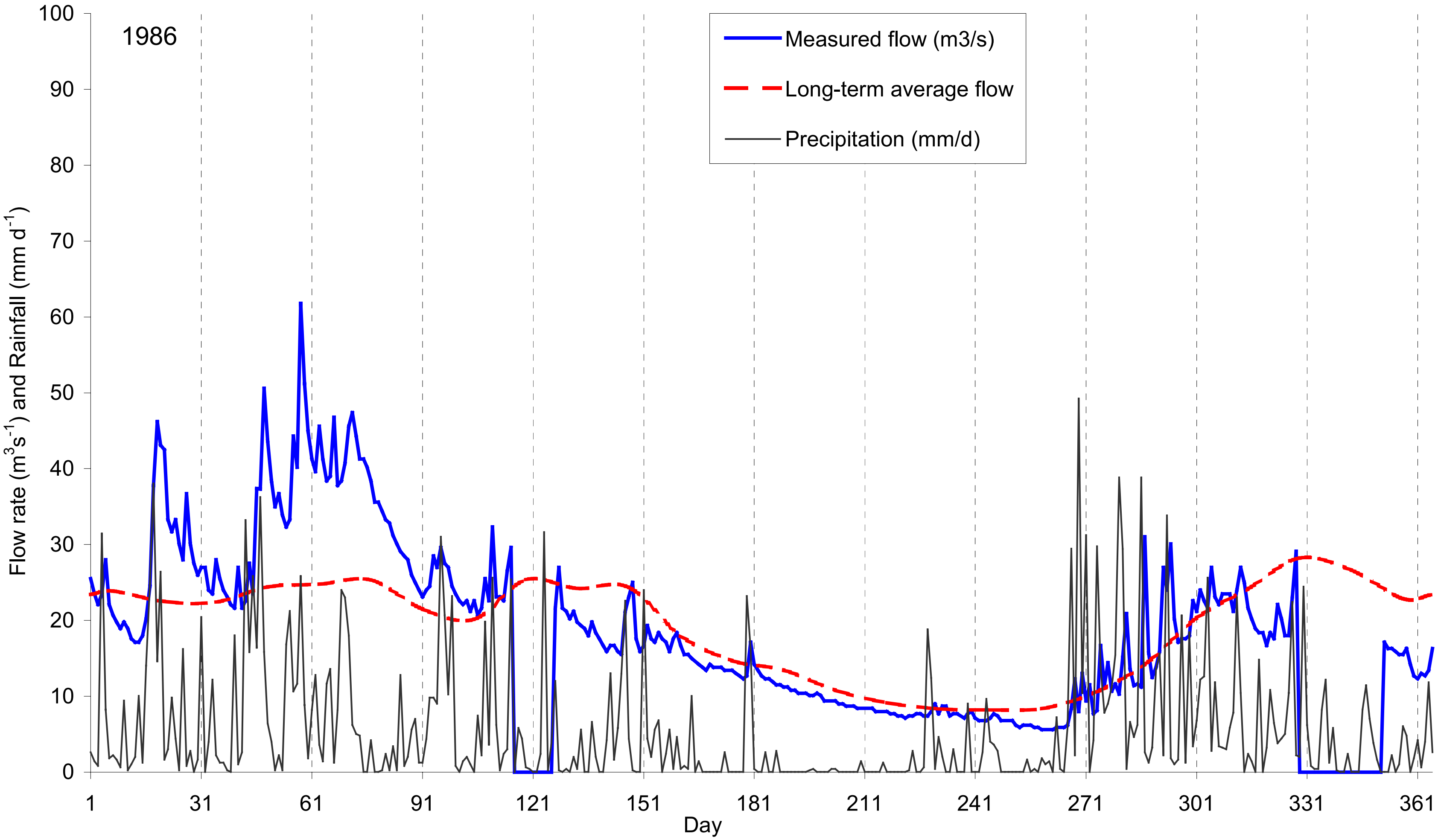



Figure E-12. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1986. Annual precipitation was 2,127 mm. Average river flow was 19.8 $m^3s^{-1}$ (corresponds to 1,014 mm $yr^{-1}$).

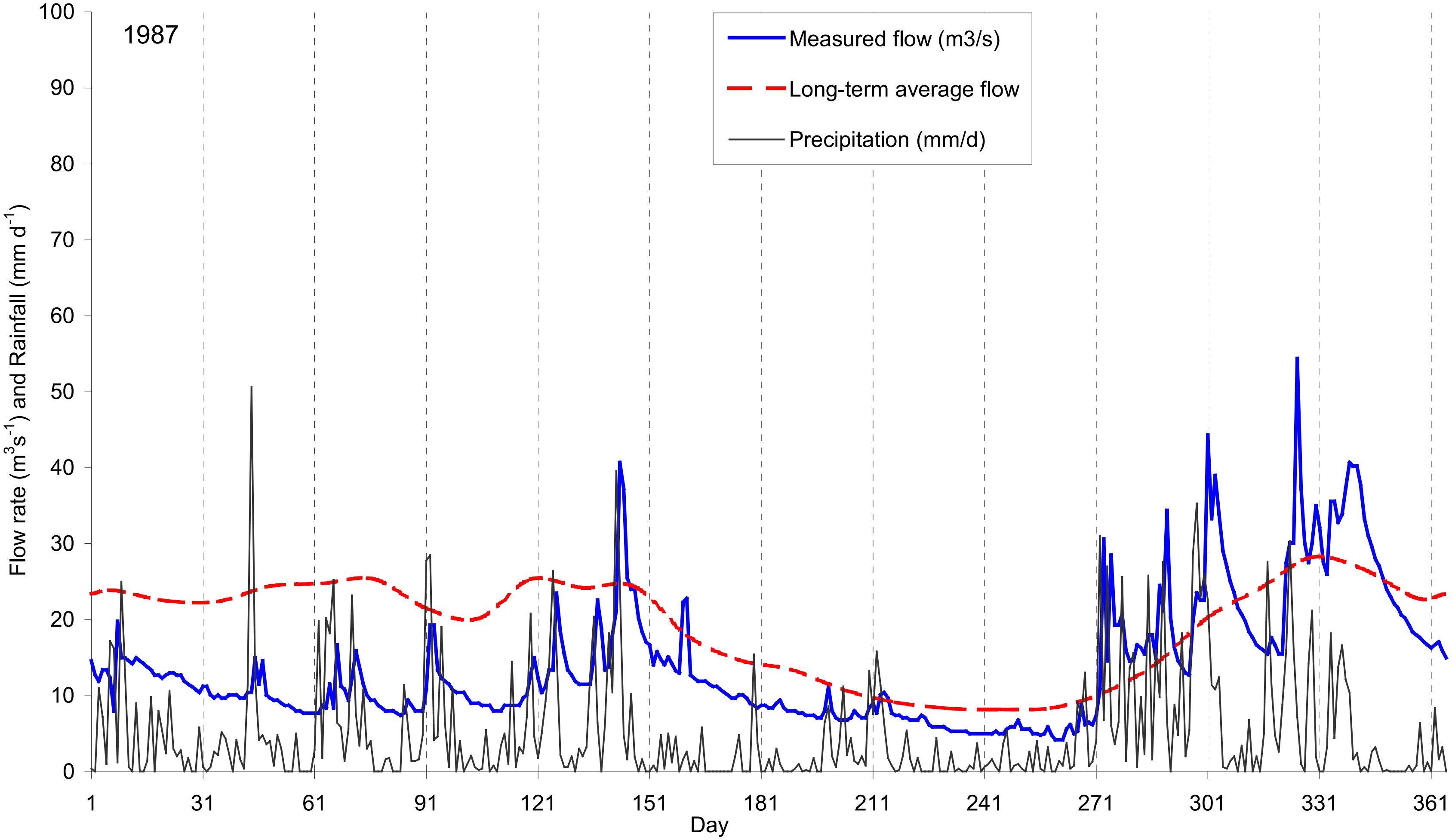



Figure E-13. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1987. Annual precipitation was 1,903 mm. Average river flow was 13.7 $m^3s^{-1}$ (corresponds to 704 mm $yr^{-1}$).

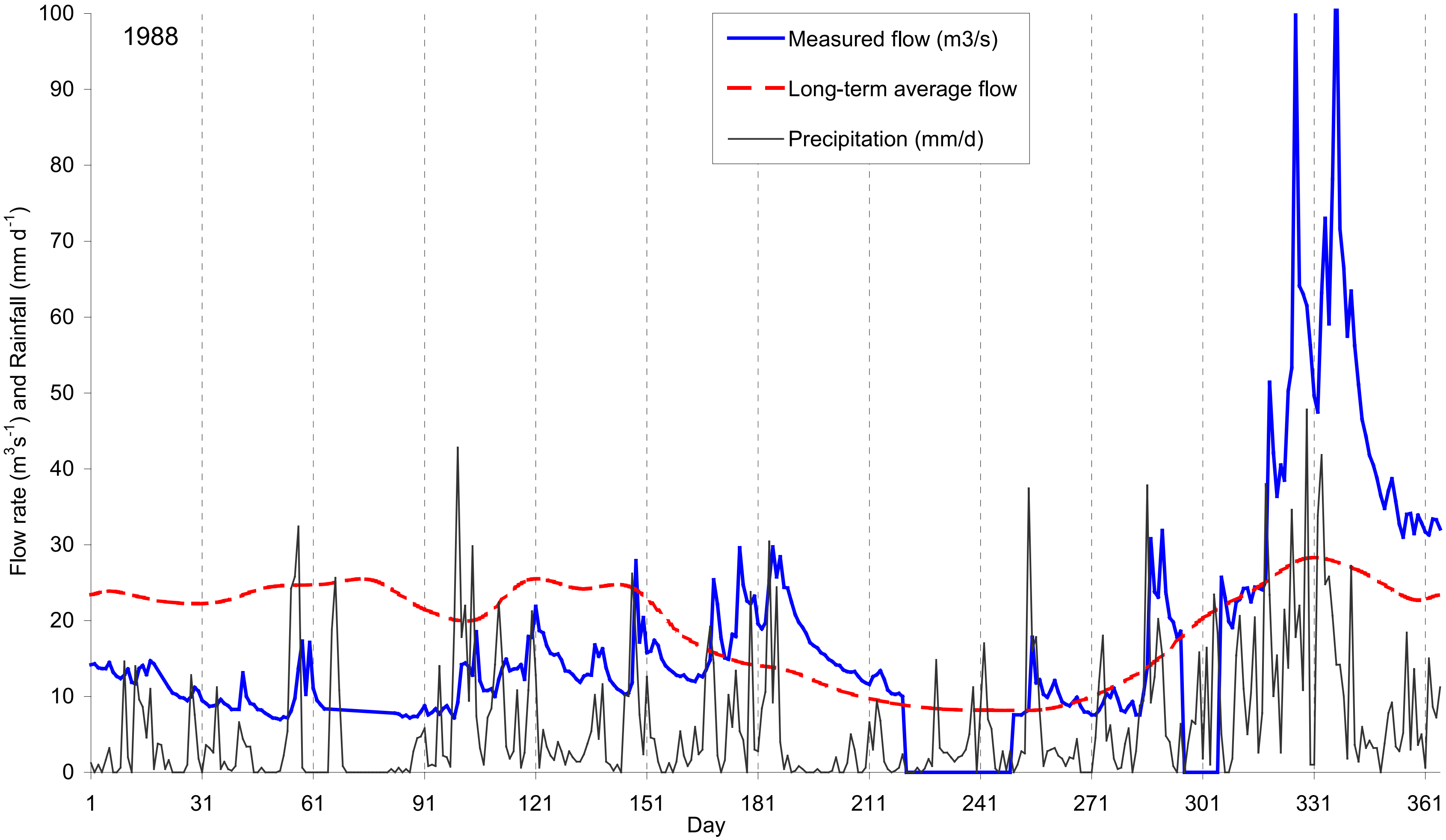



Figure E-14. Daily measured flow rate of the Ovejas River and precipitation in the Ovejas River watershed in 1988. Annual precipitation was 2,281 mm. Average river flow was 17.8 $m^3s^{-1}$ (corresponds to 914 mm $yr^{-1}$).

# APPENDIX F
# DESCRIPTIONS OF SCENARIOS

Three scenarios for the Cabuyal River watershed have been developed. They were based on similar scenarios that E.B. Knapp (1999, personal communication) developed for a watershed in Nicaragua and presented at a local stakeholder workshop in Managua, May 1999. The scenarios describe contrasting but plausible futures of the watershed in the year 2025. Figure F-1 shows the geographic extent of the administrative Cabuyal region and its 22 communities, Cabuyal River, and Pan-American Highway. This map makes it easier to understand some specific spatial references that are given in the descriptions of the scenarios.

## Corporate Farming Scenario

### Economy

This year marks the twenty-fifth anniversary of the “New” Common Market of Central and South America. During the first decade of the 21$^{st}$ century the world witnessed extraordinary increases in demand for agricultural and manufactured goods by China and India to the point that almost all agricultural and industrial capacity in Asia is now used to serve food demand within Asia. The United States and Europe turned their attention more towards Latin America in search of the capacity to supply the needs of their consumers.

While the nation of Colombia survived as the central unit of governance, global and regional liberalization in pursuit of economic growth has resulted in dominance of virtually all economic sectors by stateless corporations with little allegiance to any country. Industrial activity in the Cabuyal watershed is now dominated by a variety of agri-businesses that produce, process and market sugarcane, fresh vegetables like tomato and peppers, coffee and to a lesser extent cassava. Intensive cattle ranching takes place too. The watershed has developed as one of the most important vegetable production areas in the Cauca region.

The city of Pescador is now the most important industrial city in the larger, 100,000 ha Ovejas watershed. Pescador gained this position as it greatly benefited from its favorable location at the Pan-American Highway and a well-developed infrastructure that provided quick access to other parts of the Cabuyal River watershed. From here agricultural products could be transported quickly to distribution centers and regional markets in Popayan and Cali.

Large sugar companies salinated the valley lands and depleted the ground water in the valleys. In search for more productive land and additional water supplies, sugarcane production expanded to mountainous areas and higher elevations. Large sugarcane companies bought up almost 80% of the land area in the lower and middle part and about 40% in the upper part of the Cabuyal River watershed. Sugarcane production is characterized as high-tech but still requires a significant amount of human labor because it is difficult to use heavy machinery on the steep slopes. Therefore, the demand for human labor remained high in the area.

Interest in the production of irrigated high-value crops such as tomato, peas and peppers also grew during the first decade of the millenium. Farmers preferred to grow vegetables because they have a high market value and because research in the region indicated that cropping schemes that included irrigated tomato increased long-term farm sustainability (Hansen, 1996). In 2010, a new system of cheap bank loans allowed farmers to invest in irrigation equipment that was more efficient and had a large capacity. Many farmers cooperated to collectively purchase larger quantities of pesticides at a discounted price and shared irrigation equipment. These groups of farmers gradually merged and developed into what are now referred to as horticultural farms. The annual income and living standards of these horticulture farmers are among the highest in the region.

Some analysts point to two worrisome trends. First is the potential for growing political tensions between stateless corporations and the nation-state. The stateless corporations may be an initial source of foreign exchange for a country and are part of the backbone of Colombia's industry, but they also have a history of internal political manipulation. Secondly, although national indicators like GNP and economic infrastructure suggest that Colombia is wealthier by far now than ever, there is growing inequality between the poor and the rich. Nowhere can this be seen more than the contrasts in between the urban areas like Popayan and Cali and the rural areas in the Cabuyal River watershed.

Demography

The direction of development of the Cabuyal River watershed, particularly the area around Pescador, resulted in considerable demographic and societal changes. Today, relatively few families are living on their farms due to the fact the land is 90% owned by absentee owners. The communities of Pescador, Crucero, Ventenas, Panamericana and Santa Barbara now carry about 50% of all inhabitants of the watershed. This was 26% in 1990.

High technology agriculture has resulted in good employment opportunities for a limited number of agricultural engineers and agronomists in the industries and some farms. There is considerable demand for low-tech labor in the sugarcane and vegetable fields all year around. Many field workers live in urban areas and travel to the fields on a daily basis.

The limited number of opportunities for technical jobs and the tough work in the fields has resulted in tensions between families of the educated group of well paid technical people and the rest of the community. As a consequence, there is a continuous exodus of people from the watershed to the larger urban centers of Cali (70 km north) and Popayan (40 km south).

Landscape.

Rural land use throughout Colombia and specifically in the Cabuyal River watershed changed dramatically. Most forest was cut for wood production, to extend the area under sugarcane and crop production, or to create space for industries and houses. Most of the remaining forest can now be found on steepest hill slopes (> 15% slope) and in the most remote areas (> 500 m from road and houses). Economic and conservation incentives to deforest part of the watershed, particularly near streams and springs, were non-existent.

Sugarcane plantations can be found in areas that are relatively flat and that have good access to roads. The sugarcane companies have bought most of the land that meets these requirements. Vegetable production takes primarily place in the close proximity of farms and streams. This facilitates the supply of irrigation water on a regular basis. Coffee is grown under a variety of conditions and most of the land in the watershed is suitable for coffee production.

The area under pasture has remained at the same level as in 30 years ago, covering some 36% of the land. The distribution of pasture has somewhat changed, the most significant change is in the use of pasture. Increases in individual wealth, even of a relatively few, and the demand for land by agribusiness have increasingly driven up land prices over the past 10 years. As a consequence of the expensive land cattle ranching is now high-tech. The hillsides have been divided up into five hectare paddocks with a stocking density of 10 head per hectare. New breeds of hybrid cattle developed specifically for Latin American conditions are systematically rotated between paddocks. Paddocks are very intensively managed and generally irrigated.

Older inhabitants remember that water used to be a practically free resource of which large quantities were available. In the 1990s and the early 2000s, families only had to pay a fixed monthly fee to have access to a drinking water system. The charge varied from 200 to 1500 pesos and had to be paid to the local drinking water committees, which was responsible for the management and maintenance of the different drinking water system. Once paid, as much water could be used as needed for domestic purpose. However, an increasing fraction of drinking water was used for irrigation of vegetables. Although this was an illegal practice, the water use rules were not enforced and farmers were not sanctioned. Other farmers pumped unlimited volumes of water directly out of the river. The industrial sector extracted growing volumes of water to process their products and routed part of the water back to the river. Slowly the situation grew out of hand. There were increasing conflicts about insufficient water supply in the drinking water system and in the river and the local population expressed growing concern about decreasing water quality.

As a response to these problems, the poorly managed local aqueduct committees were replaced in 2007 by a central water planning authority. The *Laguna-Pescador*, *El Cidral* and *Santa Barbara* drinking water systems, which take water from the Cabuyal River (Table 4-3), were reconstructed. Use of wider pipes and newly designed water intakes more than doubled the combined capacity of the three system to 40 L/s. It was thought that this capacity were sufficient to serve all domestic, industrial and agricultural water needs.

Water consumers were charged a volumetric tariff. The rate was dependent on the type of water use and the time of the year. Households had to pay the highest tariffs because the government did not want domestic water use to compete with agricultural and industrial water use. Water tariffs were highest during the dry season when demand for irrigation water high. Unfortunately, the capacity of the system appeared insufficient to meet the quickly growing irrigation water demand. Moreover, the system of volumetric tariffs failed because water users manipulated the metering and cost for administration was unacceptably high. The vegetable farmers and corporate managers put pressure on the government to come up with an alternative.

In 2010 the national government selected the flourishing Cabuyal River watershed as one of few case study regions for a new water management initiative. Volume tariffs were abolished and the drinking water systems were to serve domestic water demand exclusively. The water planning authority constructed major dams at six places in the Cabuyal watershed. Each dam is connected to a large external basin with an approximate storage capacity of 150,000 $m^3$. Construction of these large basins in the hilly landscape was something rare and meant a challenge from engineering and architectural standpoints.

The basins were gradually filled during the wet season. From June through September, vegetable farmers and agricultural industries could use water from these basins for free. They only had to invest in irrigation equipment themselves, which many farmers did cooperatively. In addition to supplying irrigation water, the dams also functioned as water buffers during heavy storms and reduced the risk of flooding of fields near the streams.

## Ecological Watershed Scenario

### Economy

The United Nations Conference on Environment and Development (UNCED) and Agenda 21 made policy makers worldwide aware of the need to rapidly deal with global environmental problems and to accelerate sustainable development. The developmental and environmental objectives of Agenda 21 required a substantial flow of new and additional financial resources to developing countries in order to cover the incremental costs to implement development plans and to strengthen the capacity of international and national institutions.

Agenda 21 did not have any impact on the management of the Cabuyal River watershed until after the century change. Degradation of the fragile hillsides agro-ecosystems continued as a consequence of decisions that led to deforestation, overgrazing and destructive agricultural practices. Farmers kept focussed on the short-term benefits of alterations in the landscape and management practices. Authorities failed to create any incentives for farmers to invest in long-term conservation measures. The few conservation projects that were carried out were on a voluntary basis and coordinated by researchers and engineers from CIAT and CIPASLA (the Inter-Institutional Consortium for Sustainable Agriculture in Hillside). In one of these projects natural buffer zones were created near streams and around major springs.

All this changed in 2002. The change resulted from two important policy-related milestones that occurred almost concurrently. The first and most important event was an agreement among the economically strong countries of North America and Europe who were increasingly concerned about the man-made causes of environmental degradation, loss of biodiversity, and global climate change. The rich countries had created a system of "carbon bonuses." The strategy, technically called "transfer payments," was used in place of paying for expensive technologies to control $CO_2$ emitted by their industries, companies in the rich countries could buy "bonds of carbon" from poor countries to help conserve the environment by forestation and creation of wetland areas. It is well known that forests acts as environmental filters for $CO_2$ and that wetlands can filter nitrates from potential acid rain and leached chemicals. This creates a cleaner environment, improves the natural resource base and enhances biodiversity.

Because the Colombian government did not receive funding for technical assistance of the "carbon bonuses" project, agriculture did not change course to the point where it could economically and technologically compete significantly with high value, high quality agricultural commodities in the "global free-market place." As a consequence, the federal government strongly committed Colombia to a policy of selling "carbon bonuses." The government set up large protected areas in the uninhabited Amazon jungle in the southeastern part of the country negotiated the first contracts. This resulted in some revenue for the federal government.

Unfortunately, there were many conflicts with indigenous groups who disagreed on the future of their land. Corruption within the federal government resulted in numerous malicious carbon bonus contracts. In an attempt to address these issues, community-level user organizations in collaboration with regional authorities were given the right to negotiate contracts with foreign companies in 2008. All powers were dissolved, including formal rights of community ownership of infrastructure. The rich countries, however, only paid the minimum price needed to purchase contracts. The revenues from selling contracts was more than the government would receive from taxes from the marginally productive agricultural and forest products sectors, but not enough to contribute significantly to social and economic development. This caused a dilemma. Since "carbon forests" generated almost no employment, the percentage of unemployed and under-employed in the Cabuyal River watershed did changed since 1999, and as a consequence of a doubling of the population, the unemployment today is twice that in 1999.

In an attempt to alleviate the unemployment problem, the government has promoted unskilled, labor intensive jobs in agriculture like manual harvesting of irrigated sugarcane and cotton. Also found in the flat, irrigated land are vegetable farms that supply the national market and absorb some manual labor. On the positive side, the federal government of Colombia has kept its intentions to “strengthen decentralization, local participation and the homogenization of policies and strategies for the rural sector so as to guarantee greater efficiency and transparency in the use of resources”. As a result, governance at all levels is very democratic.

The second milestone was associated with the Ovejas River Watershed. Already in 1991, the Cauca Valley Corporation (CVC) proposed a plan to divert water from the larger Ovejas River to the Salvajina dam to benefit an existing hydropower plant (Estrada, 1993). Because of lack of financial means and protests by local population, construction of the underground water channel did not start until 2003 and was completed within 4 years. CVC had a mandate to sustain minimum river flows in the dry season and to reduce peak river flow rates on rainy days. The former is important to meet requirements for water contribution to the hydropower plant, the latter is important to prevent erosion of riverbanks and build-up of sedimentation in the underground water channel.

CVC had two main approaches to achieving these management goals. The cultivation of irrigated crops was discouraged by actively enforcing the policy that water from the drinking water system should exclusively be used for domestic purposes. Farmers who used pumps to extract water directly from the river were assigned very limited times on which to irrigate and the pumps had not to exceed a certain capacity. Violators were given stiff fines.

On the other hand, farmers received substantial financial incentives to reforest part of their land and avoid fallow land on steep hill slopes. These measures were to reduce the potential for soil erosion and build-up of sedimentation. Purchases of seeds and fertilizers were partially subsidized as well. This allowed farmers to use large quantities of production inputs and obtain higher yields of conventional crops like maize, beans and cassava. Engineers and agronomist from the CVC assisted farmers in developing new land use plans and testing new varieties.

The second approach involved the development of “check dams” along the streams. These dams function as a series of water buffers that increasingly smoothen the flow rate of water along its downstream flow path, resulting in a reduction in the frequency and severity of the floods of the riverbanks in the lower parts of the watershed. The check dams had to have a large combined water storage capacity. This could be achieved by building either numerous small dams or a limited number of larger dams. CVC chose the first option, because it was easier to construct smaller dams in the hilly landscape of the Cabuyal watershed.

Demographics

Today there are almost no families living on their farms. What one finds now are eight small "conjuntos” of up to 1500 people in which 90% of the inhabitants live. Four conjuntos are located in the middle of the watershed near the Pan-American Highway, two in the lower part and two in the upper part. The town of Pescador developed into the largest conjunto. Some towns that existed thirty years ago do not exist today and there are no new communities.

Why is this so? Because of the system of carbon bonuses, community-level user associations were given significant powers to define rules and norms for use of resources within the watershed/landscape and to manage the process of local-level resource monitoring. The strict land management policies motivated many families to move off the farm and into one of the conjuntos, where living conditions are generally better, clean drinking water is available in each house, and a good infrastructure and a variety of shops are offered.

Landscape

Young forest and shade tolerant crops now dominate the landscape. Shade-grown traditional varieties of coffee are promoted and intensively cultivated crops like bean and maize in the 1990's are rare. There is a new resintapping cooperative in the Pescador community that is taking advantage of areas that used to be in annual crops and pasture but are now reforested in pine. There are also some experiments being carried out by a local group of farmers on the production of pine nuts and forest mushrooms for export.

No "scientific" study has been carried out, but on close examination, one finds important differences between the eight conjuntos in the watershed. If you ask residents, you learn that at the initiation of the system of transfer payments, local user associations of three communities chose to immediately distribute all payments among their members while members of five village associations chose to pool some of their payments to create a trust fund. Revenue generated by the trust fund was used for local resource monitoring and public works.

The trust fund has partly paid for the extensive development of "check dams" along the streams. These dams reduce the velocity of water, limiting the frequency and severity of the floods of the river banks in the lower parts of the watershed. As a result of the system of check dams, the soil eroded from the stream banks settled behind the dams. In a surprisingly short time, small but extremely fertile plots are created. It is in these small plots that intensive home gardens produce vegetables for the local market.

As a result of improved regulation of flow rates, in 2012 the five communities began constructing wetlands at strategic places around the watershed. With technical assistance offered by CVC, local communities constructed "vertical flow wetlands" which provide maximum contact between roots of aquatic plants, and macro and micro fauna with waste water from the conjuntos. Performance in reducing biological oxygen demand (BOD) and suspended solids and pathogenic microorganisms is equal or better than conventional treatment plants. The simplicity and low costs of these systems offered much to small communities especially in the range of 1000 people down to a single family.

Even though not all villages in the watershed are managing the transfer payments in the same manner, in general the landscape throughout the Cabuyal River watershed has more forest cover and is better managed compared to twenty years ago. Water flow through the watershed has become more predictable and less erratic over the years. The watershed is known throughout Colombia for the pure water and uncontaminated air.

## Business as Usual Scenario

### Economy

In January 1998, the Government of Colombia prepared and presented a project called “A Road Map for Modernizing Rural Colombia” to a consortium of European donors for funding. Before a decision was made to fund the project, Hurricane Mitch hit Central America in Fall 1998 and the war in Kosovo took place in Spring 1999. The European Union and the United States decided to help the victims of the war and the natural disaster. The rural development plan was never funded nor carried out. Over the past 25 years, the rural agricultural sector and the general economy have developed with little financial support, governance and direction.

The original development plan intended to “promote the establishment of transparent markets in the commercialization and price spheres”. Today, a large number of producers and a small number of companies with international connections characterize almost all commercialization of agricultural products in Colombia. This gives the companies relatively more economic and negotiating power compared to the small producers.

The small number of corporate managers and powerful brokers is an exclusive club of people who know that they will make extra profits when international prices are high if they do not immediately pass on the increases to the farmers as higher domestic prices. Because there is a large number of buyers for high volume, low quality agricultural commodities, and because it is less effort than meeting strict quality requirements, no attempt has been made to educate and train Colombian farmers in technologies to produce high quality and high value commodities.

Most inhabitants are grandparents, grandchildren and their mothers. Many husbands and young men have left to search for work elsewhere, primarily in other Latin American countries. There was a time when they could enter the United States without too many problems and earn good money to send back to their families. Now, however, the United States has become very strict and almost no one can even visit any more.

A study carried out last year by the University and Ministry of Health seems to verify what local residents of the watershed have been saying for some time. The general level of health of the population is worsening rapidly. Of primary concern is the high number of cases of undiagnosed intestinal problems, which many local residents attribute to unsatisfactory water and sanitation management. A general feeling of lack of opportunity and declining health has resulted in low school attendance by the children.

## Demography

Some families or heads-of-households have moved to urban parts of Colombia to start a new life or search for employment to generate additional cash for the family. Unfortunately, the continuous unstable political situation and the staggering national economy had a dramatic effect on unemployment and crime in the Colombian cities, which are now among the worst ever in Latin American history. This has driven people back to the rural areas like the Cabuyal River watershed, even though these areas offer little hope for improvement. Consequently, the growth rate in the rural areas has been twice as high as in the cities. Houses can be found scattered throughout the landscape, even in remote areas. The high rate with which people move around, build houses and vacant them has caused a disintegration of villages and communities.

Landscape

The landscape of the watershed is typical of the many rural regions of Colombia and other Latin and Central American countries. There have been few changes in the landscape pattern since 1990, except for the large-scale disappearance of forest. The landscape is still extremely heterogeneous and consists of many small agricultural plots on which a variety of crops are cultivated – maize, beans, cassava, tomato and plantain. Most products are exclusively for family consumption, although some farmers grow some irrigated vegetables that are sold on local market. All families manually irrigate small homemade orchards and vegetable plots of 0.1 ha. Coffee is hardly grown in the watershed. The area pasture has remained fairly constant, but it is used more intensively than before. Farmers have invested in livestock (500% increase in 25 years) to produce dairy products and meat for home consumption.

Only about 22% of all natural forest in 1990 remain today. Most of it can be found in the upper part of the watershed. Farmers have been cutting the forest in search for additional cropland and firewood. This is comparable to slash and burn practices that take place in many other developing countries. Reforestation does not take place because of a lack of incentives for local stakeholders and absence of any conservation projects.

Many families do not own the land they farm anymore. The poor living conditions and the incapacity of the proprietor to improve the productivity and the quality of the life of families forced many people to change land use and land ownership. If they did own the land at one time, it was sold, leased or abandoned to raise money to live on. Some families plant some bean and maize on very poor land that has degraded to the extent that the original owners abandoned it.

In 2001, the government of Colombia adopted a new national policy to transfer management of natural resources, specifically forests and water, to user associations. It was thought that this would gradually improve the state of water and forest resources and reduce conflicts about their use. The government maintained considerable advisory influence and exercised some control over operations and management and budgets for years. In 2009, a second law relaxed control over management, however powers devolved did not include formal rights of community ownership of infrastructure. More importantly it is not clear whose responsibility it is, and what terms exist to finance costs of rehabilitation of infrastructure and maintenance of critical forested drainage areas.

Private individuals cannot own important springs feeding public water supplies. However, land immediately surrounding the springs can be privately owned. An emerging trend is that land owners are building fences around the springs effectively isolating them from public access, monitoring and maintenance. As a result, water intake by the drinking water systems is seriously threatened at any time of the year and stream flows are very low during the summer. Some 85.2 % of the population of the Rio Cabuyal watershed benefited from the drinking water systems in 1990. A total of 2714 people (51.2% of population) were served by drinking water systems that drew water within the catchment and 1821 people (34.0%) ha access to drinking water systems that originated outside the catchment area. The absolute numbers have not significantly changed in 2025. However, as population grew considerable, this means that only 50% of the inhabitants have access to clean drinking water today. The remaining inhabitants take water directly from the river or use private wells.

The stagnant economic growth of agriculture around the watershed caused much of the most productive labor force to leave and reduced care to prevent environmental degradation. This has resulted in some tragic events. Burning is the preferred method to prepare land because it requires minimum labor and rapidly recycles scarce nutrients. Unfortunately, several times each year, fires go out of control and burn whatever is in their path, including neighboring agricultural crops and residences. The large area of fallow land and lack of soil conservation and erosion prevention result in major land slides during high rainfall events. On average 20 families lose their entire property (house or agricultural plots) each year because of fires or landslides.

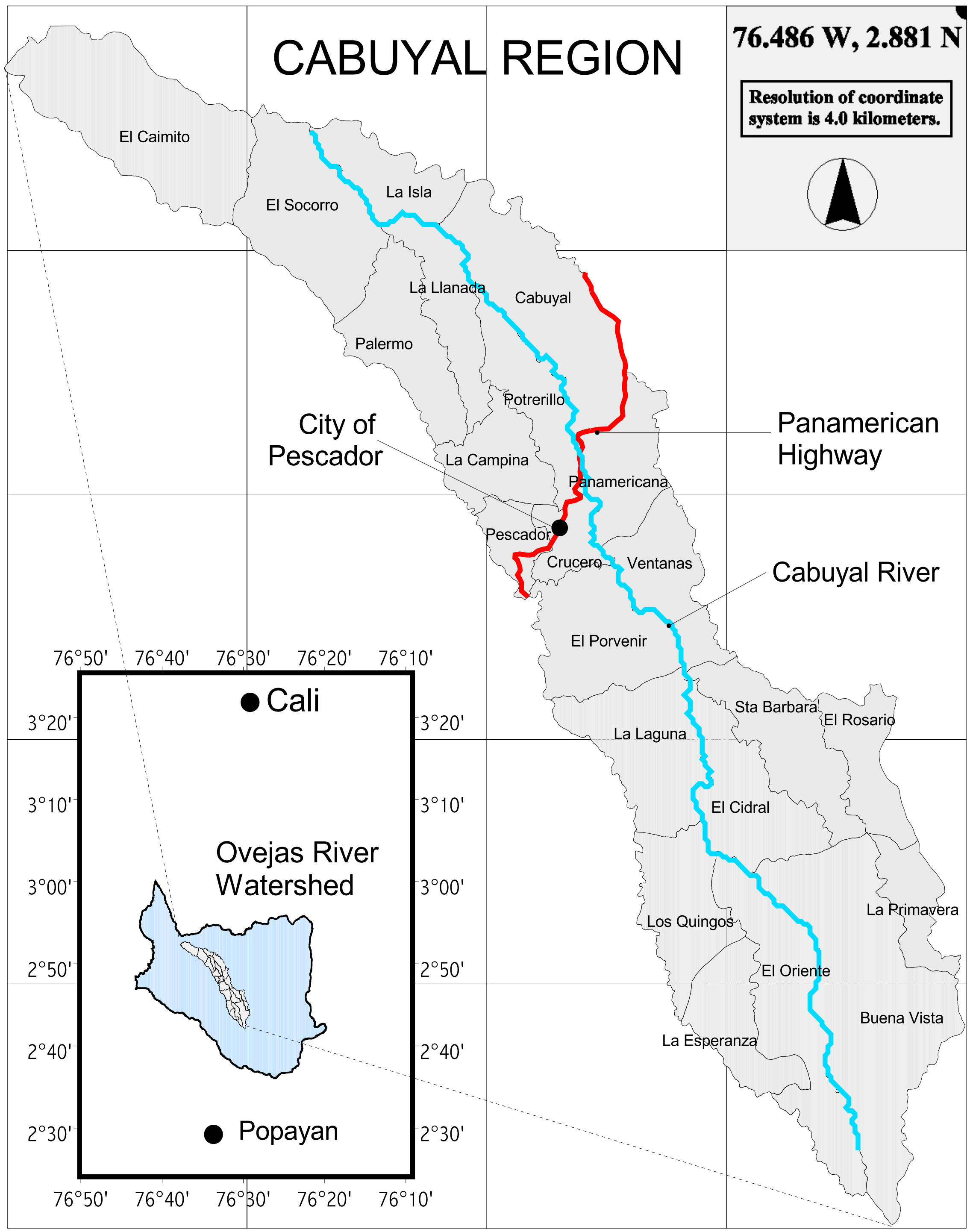



Figure F-1. Geographical location of the 22 communities that form the administrative Cabuyal region. The Cabuyal River and most of the Pan-American Highway serve as boundaries between communities.

APPENDIX G
POPULATION PROJECTIONS COLOMBIA

These population data are based on the United Nations 1996 revised population projections (United Nations, 1998). The United Nations reported data for a low, medium and high population growth scenario.

Table G-1. Annual growth rate of the population in Colombia. Data of the years 2000-2050 are based on the United Nations low, medium and high UN projections.

| Year | Actual (million) | Year | Low prj. | Med. prj. | High prj. |
|---|---|---|---|---|---|
| | | | ----------------- million | -------------------- | |
| 1950 | 11.946 | 2000 | 38.746 | 38.905 | 39.166 |
| 1955 | 13.759 | 2005 | 41.391 | 41.877 | 42.620 |
| 1960 | 15.939 | 2010 | 43.791 | 44.771 | 46.171 |
| 1965 | 18.506 | 2015 | 45.945 | 47.584 | 49.799 |
| 1970 | 21.360 | 2020 | 47.765 | 50.246 | 53.465 |
| 1975 | 23.776 | 2025 | 49.160 | 52.668 | 57.117 |
| 1980 | 26.525 | 2030 | 50.325 | 55.044 | 60.949 |
| 1985 | 29.415 | 2035 | 51.150 | 57.209 | 64.808 |
| 1990 | 32.596 | 2040 | 51.610 | 59.148 | 68.669 |
| 1995 | 35.814 | 2045 | 51.685 | 60.839 | 72.530 |
| | | 2050 | 51.380 | 62.284 | 76.405 |

Table G-2. Annual growth rate of the Colombian population. Data from the years 1995-2050 are based on the United Nations low, medium and high projections.

| Period | Actual | Period | Low prj. | Med. prj. | High prj. |
|---|---|---|---|---|---|
| | %/yr | | -----------------%/yr ------------------ | | |
| 1950-1955 | 2.87 | 1995-2000 | 1.59 | 1.67 | 1.81 |
| 1955-1960 | 2.99 | 2000-2005 | 1.33 | 1.48 | 1.70 |
| 1960-1965 | 3.03 | 2005-2010 | 1.13 | 1.35 | 1.61 |
| 1965-1970 | 2.91 | 2010-2015 | 0.96 | 1.23 | 1.52 |
| 1970-1975 | 2.17 | 2015-2020 | 0.78 | 1.09 | 1.43 |
| 1975-1980 | 2.21 | 2020-2025 | 0.58 | 0.95 | 1.33 |
| 1980-1985 | 2.09 | 2025-2030 | 0.47 | 0.89 | 1.31 |
| 1985-1990 | 2.07 | 2030-2035 | 0.33 | 0.77 | 1.24 |
| 1990-1995 | 1.90 | 2035-2040 | 0.18 | 0.67 | 1.16 |
| | | 2040-2045 | 0.03 | 0.57 | 1.10 |
| | | 2045-2050 | -0.12 | 0.47 | 1.05 |

## REFERENCES


Abdalla, C.W. and T.W. Kelsey, 1996. Breaking the impasse: Helping communities cope with change at the rural-urban interface. J. Soil Wat. Cons. 51(6): 462-466.

Agrawal, A., 1997. Community in Conservation: Beyond Enchantment and Disenchantment. Paper prepared for the Conservation & development Forum. Institution for Social and Policy Studies. Yale University, New Haven, CT.

Arnold, J.G., Williams, J.R., Nicks, and A.D., Sammons, N.B., 1990. SWRRB — A basin scale simulation model for soil and water resources management. Texas A&M University Press, College Station, TX.

Arnold, J.P., Williams, J.R., Srinivasan, R., and King, K.W., 1995. SWAT: Soil and water assessment Tool. Texas A&M University and the USDA Agricultural Research Service, College Station, TX.

Ashby, J.A., 1985. The social ecology of soil erosion in a Colombian farming system. Rural Sociol. 50 (3): 377-396.

Ashby, J.A., J.A. Beltran, M. del Pilar Guerrero, and H.F. Ramos, 1996. Improving the acceptability to farmers of soil conservation practices. J. Soil Wat. Cons. 51(4): 309-312.

Baptiste, L.G., 1994. Rural community approaches to biodiversity conservation in Colombian high mountains. Doctoral dissertation. Center for Latin American Studies, University of Florida, Gainesville, FL.

Batchelor, C., J. Cain, F. Farquharson, and J. Roberts, 1998. Improving water utilization from a catchment perspective. SWIM paper 4, International Water Management Institute (SWMI), Colombo, Sri Lanka.

Batchelor, W.D., Dillaha, T.A. III, Wolfe, M.L., Heatwhole, C.D., and Mostaghimi, S., 1994. A farmscale water quality planning system for evaluating best management practices. Presented at the 1994 ASAE Internal Summer Meeting, June 19-22, Kansas City, KS. ASAE Paper No. 94-2160. ASAE, 2950 Niles Road, St. Joseph, MI.

Bates, C.B. and P.K. Davies, 1988. Effect of baseflow separation procedures on surface runoff model. J. Hydrol. 103: 309-322.

Black, P.E., 1996. Watershed hydrology. 2nd ed. Ann Arbor Press, Chelsea, MI.

Bouraoui, F. and T.A. Dillaha II, 1994. ANSWERS2000: Continuous simulation version. Presented at the 1994 ASAE International Summer Meeting, June 19-22, 1994, Kansas City. ASAE paper 94-2154, ASAE, 2950 Niles Road, St. Joseph, MI.

Bouma, J., 1997. The role of quantitative approaches in soil science when interacting with stakeholders. Geoderma 78: 1-12.

Bosch, D.D., R.L. Bingner, F.D. Theurer, and G. Felton, 1998. Evaluation of the AnnAGNPS water quality model. Paper presented at the 1998 ASAE Annual International Meeting, July 12-16, Orlando, FL. ASAE Paper No. 98-2195. ASAE, 2950 Niles Road, St. Joseph, MI.

Bosch, J.M. and J.D. Hewlett, 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55: 3-23.

Bromley, D.W. (ed.), 1992. Making the commons work: Theory, practice, and policy. Institute for Contemporary Studies, San Francisco, CA.

Brooks, K.N., P.F. Fflolliott, and H.M. Gregersen, 1997. Hydrology and the management of agricultural watersheds. Iowa State University Press, Ames, IA.

Bruijnzeel, L.A. and K.F. Wiersum, 1987. Rainfall interception by a young Acacia Auriculiformis (A. Cunn) plantation forest in west Java, Indonesia: application of Gash's analytical model. In: Hydr. Process. (1): 309-319.

Burrough, P.A., 1986. Principles of geographic information systems for land resources assessment. Clarendon Press, Oxford, UK.

Burrough, P.A. and R.A. McDonnell, 1998. Principles of geographical information systems. Oxford University Press, Oxford, UK.

Byne, S., 1996. An evaluation of the accuracy of DEM-derived altitude and slope values. Unpublished report. International Center for Tropical Agriculture, Cali, Colombia.

Calder, I.R., 1982. Forest evapotranspiration. In: Canadian Hydrology Symposium: 82. Associate Committee on Hydrology, National Research Council for Canada. Ottawa, ON. pp 173: 193.

Calder, I.R., 1998. Water resource and land use issues. System-wide Initiative on Water Management (SWIM), Paper 3. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Chen, H. and R.Beschta. 1999. Dynamic hydrologic simulation of the Bear Brook Watershed in Maine (BBWM). Environmental Monitoring and Assessment 55: 53-96.

CIAT, 1993. Informe del taller de planificacion. (Workshop on Participatory Planning by Objective). Programa de Desarrollo Sostenible en Laderas. March 15-19, International Center for Tropical Agriculture (CIAT), Cali, Colombia,

CIAT, 1996. CIAT hillsides program. Annual report 1994-1995. International Center for Tropical Agriculture (CIAT), Cali, Colombia.

CIAT, 1997. Community-led management of watershed resources in hillside agro-ecosystems of Latin America. Annual highlights for project PE-3, October. International Center for Tropical Agriculture, Cali, Colombia.

Conese, C., M.A. Gilabert, F. Maselli, and L. Bottai, 1993. Topographic normalization of TM scenes through the use of an atmospheric correction method and digital terrain models. Photogram. Eng. Rem. Sens. 59(12): 1745-1753.

Cronshey, R.G., F.D. Theurer, and R.L. Glen, 1996. GIS water-quality model interface: A prototype. In: Goodchild, M.F., L.T. Steyaert, B.O. Parks, C. Johnston, D. Maidment, M. Crane, S. Glendinning (Eds.), GIS and environmental modeling: Progress and research issues. GIS World Books, Fort Collins, CO. pp 287-291.

DeVantier, B.A. and A.D. Feldman, 1993. Review of GIS applications in hydrologic modeling. J. Wat. Res. Plan. and Manage. 119(2): 246-261.

Dillaha, T.H., M.L. Wolfe, A. Shirmohammadi, and F.W. Byne, 1998. ANSWERS 2000. Paper presented at the ASAE Annual Meeting, July 12-16, Orlando, FL. Paper no. 98-2199. ASAE, 2950 Niles Road, St. Joseph, MI.

Doorenbos, J. and W.O. Pruitt, 1977. Guidelines for predicting crop water requirements, FAO Irrigation and Drainage Paper 24, Food and Agricultural Organization of the United Nations, Rome, Italy.

Ekstrand, S., 1996. Landsat TM-based forest damage assessment: Correction for topographic effects. Photogram. Eng. Rem. Sens. 62(2): 151-161.

Engel, T., G. Hoogenboom, J.W. Jones, and P.W. Wilkens, 1997. AEGIS/WIN: A computer program for the application of crop simulation models across geographic areas. Agron. J. 89(6): 919-928.

ESRI, 1994. Cell-based modeling with GRID. Environmental Systems Research Institute, Redlands, CA.

ESRI, 1996a. Avenue, customization and application development for ArcView. Environmental Systems Research Institute, Redlands, CA.

ESRI, 1996b. ArcView spatial analyst. Advanced spatial analysis using raster and vector data. Environmental Systems Research Institute, Redlands, CA.

ESRI, 1997a. Understanding GIS. The ARC/INFO method. Version 7.1 for Unix and Windows NT. Environmental Systems Research Institute, Redlands, CA.

ESRI, 1997b. Getting to know ArcView GIS. The geographic information system for everyone. Environmental Systems Research Institute, Redlands, CA.

ESRI, 1997c. Arc macro language workbook, with CD. Environmental Systems Research Institute, Redlands, CA.

Estrada, R.D., 1993. Planteamiento y resolucion de conflictos en la cuena del Rio Ovejas. Centro Internacional de Agricultura Tropical (CIAT), Cali, Colombia.

Falkenmark, M., J. Lundqvist and C. Widstrand, 1989. Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development. Nat. Res. Forum 13(4): 258-267.

Fraisse, C.W., K.L. Campbell, J.W. Jones, W.G. Boggess, B. Negahban, 1994. Integration of GIS and hydrologic models for nutrient management planning. In: National Conference on Environmental Problem Solving with GIS, September 21-23. Seminar Publication number EPA/625/R-95/004. U.S. EPA Office of Research and Development, Washington, DC. pp 283-291.

Fraiture, C. de, J. Rubiano, C. Alvarez, 1997. Actual versus potential water use in the Cabuyal watershed - Colombia. February. IIMI-CIAT, Cali, Colombia.

Fresco, L.O., 1994. Imaginable futures: A contribution to thinking about the use of planning. In: Fresco, L.O., L. Stoorsnijder, J. Bouma, and H. van Keulen (Eds.), The future of the land. Mobilising and integrating knowledge for land use options. John Wiley, New York. pp 1-8.

Fresco, L.O., L. Stoorsnijder, J. Bouma, and H. van Keulen (Eds.), 1994. The future of the land. Mobilising and integrating knowledge for land use options. John Wiley, New York.

Gash, J.H.C., 1979. An analytical model of rainfall interception by forests. Quart. J. Roy. Meteor. Soc. 105: 43-55.

Gleick, P.H. (ed.), 1996. Basic water requirements for human activities: Meeting basic needs. Wat. Internat. 21(2): 83-92.

Gleick, P.H., 1998. The world's water. The biennial report on freshwater resources. Island Press. Washington, DC.

Goodchild, M., 1993. The state of GIS for environmental problem-solving. In: Goodchild, M., B. Parks, and L. Steyaert (Eds.), Environmental modeling with GIS. Oxford University Press, New York. pp 8-15.

Haan, C.T., H.P. Johnson and D.L. Brakensiek (eds.), 19982. Hydrlogic modeling of small watersheds. ASAE Monographs number 5. ASAE, St. Joseph, MI.

Hamilton, L.S., 1985. Overcoming myths about soil and water impacts of tropical forest land use. In: S.A. El-Swaify, W.C. Moldenhauer, and A. Lo (eds.), Soil erosion and conservation. Soil Conservation Society of America, Ankemy, IA. pp 680-690.

Hanna, S., 1995. Efficiencies of user participation and natural resource management. In: S. Hanna and M. Munasinghe (eds.), Property rights and the environment. Social and ecological issues. Beijer International Institute of Ecological Economics, Stockholm, and The World Bank, Washington, DC. pp 59-67.

Hanna, S. and M. Munasinghe (eds.), 1995. Property rights and the environment. Social and ecological issues. Beijer International Institute of Ecological Economics, Stockholm, and The World Bank, Washington, DC.

Hansen, J.W., 1996. A systems approach to characterize farm sustainability. Doctoral dissertation. Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL.

Hansen, J.W. and J.W. Jones, 1996. A systems approach for characterizing farm sustainability. Agric. Syst. 51(2): 185-201.

Hansen, J.W., E.B. Knapp, and J.W. Jones, 1997. Determinants of sustainability of a Colombian hillside farm. Expir. Agric. 33: 425-448.

Hardin, G., 1968. The tragedy of the commons. Science 162: 1243-1248.

Hayes, J.C. and Z. Zhang, 1998. Identification of NPS pollution using GIS and modeling. Paper presented at the 1998 ASAE Annual International Meeting, July 12-16, Orlando, FL. Paper no. 98-3149. ASAE, 2950 Niles Road, St. Joseph, MI.

Heatwole, C.D., K.L. Campbell, and A.B. Bottcher, 1987. Modified CREAMS hydrology model for Coastal Plain flatwoods. Trans. ASAE 30(4): 1014-1022.

Hogeweg, P., 1988. Cellular automata as a paradigm for ecological modeling. Appl. Math. and Comput. 27: 81-100.

Holling, C.S., 1986. The resilience of terrestrial ecosystems: local surprise and global change. In: W.C. Clark and R.E. Munn (eds.), Sustainable development of the biosphere. Cambridge University Press, Cambridge, UK. pp. 292-317.

Holmes, J.W. and E.B. Wronski, E.B., 1981. The influence of plant communities upon hydrology of catchments. Agric. Wat. Manage. 4: 19-34.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, W.D. Batchelor, W.T. Bowen, L.A. Hunt, N.B. Pickering, U. Singh, D.C. Godwin, B. Baer, K.J. Boote, J.T. Ritchie, and J.W. White, 1994. Crop models. In: G.Y. Tsuji, G. Uehara and S. Balas (eds.), DSSAT version 3, Vol. 2. International Benchmark Sites Network for Agrotechnology Transfer, University of Hawaii, Honolulu, HI. pp 95-244.

Jansen, D.M., J.J. Stoorvogel, and J.G.P. Jansen, 1997. A quantitative tool for regional land-use analysis. In: P.S. Teng, M.J. Kropff, H.F.M. ten Berge, J.B. Dent, F.P. Lansigan, and H.H. van Laar (eds.), Applications of systems approaches at the farm and regional levels, Volume 1. Kluwer, Dordrecht, The Netherlands. pp 399-411.

Jones, J.W. and J.C. Luyten, 1998. Simulation of biological processes. In: R.M. Peart and R.B. Curry (eds.), Agricultural systems modeling and simulation. Marcel Dekker, Inc. New York. pp. 19-62.

Knapp, E.B., J.A. Ashby, H.M. Ravnborg, and W.C. Bell, 1999. A landscape that unites: community-led management of Andean watershed resources. In: R. Lal (ed.), Integrated watershed management in the global ecosystem. Special Issue of Soil and Water Conservation. CRC Press, Boca Raton, FL.

Knapp, E.B., P. Urbano, W.B. Bell, and J.E. Rubiano, 1996. Changes in land cover/land use as a possible indicator of sustainable development in a hillside envrionment of the Rio Cabuyal in Cauca, Colombia. In: CIAT hillsides program, annual report 1994-1995. International Center for Tropical Agriculture, Cali, Colombia. pp 75-88.

Koning, G.H.J. de, 1998. Land use in Ecuador: A statistical analysis at different aggregation levels. Agric. Ecosys. Environ. 70: 231-247.

Lahlou, M., L. Shoemaker, S. Choudhury, R. Elmer, A. Hu, H. Manguerra, and A. Parker, 1998. BASINS version 2.0 user's manual. United States Environmental Protection Agency, publication EPA-823-B-98-006. Washington, DC.

Lal, R. (ed.), 1999. Integrated watershed management in the global ecosystem. Special Issue of Soil and Water Conservation. CRC Press, Boca Raton, FL.

Langford, M. and W. Bell, 1997. Land cover mapping in a tropical hillsides environment: A case study in the Cauca region of Colombia. Intl. J. Rem. Sens. 18(6): 1289-1306.

Maidment, D.R., 1993. GIS and hydrologic modeling. In: Goodchild, M., B. Parks, and L. Steyaert (eds.), Environmental modeling with GIS. Oxford University Press, New York. pp 147-167.

Maidment, D.R., 1996. Environmental modeling within GIS. In: Goodchild, M.F., L.T. Steyaert, B.O. Parks, C. Johnston, D. Maidment, M. Crane, and S. Glendinning (eds.), GIS and environmental modeling: Progress and research issues. GIS world books, Fort Collins, CO. pp 315-323.

McKean, M.A., 1992. Success of the commons. A comparative examination of the institutions for common property resource management. J. Theor. Pol. 4(3): 247-281.

McKinney, D.C., X. Cai, M.W. Rosegrant, C. Ringler, and C.A. Scott, 1999. Modeling water resources management at the basin level: Review and future directions. SWIM paper 6. International Water Management Institute, Colombo, Sri Lanka.

Meyer, P., K.L. Itten, T. Kellenberger, S. Sandmeier, and R. Sandmeier, 1993. Radiometric corrections of topographically induced effects on Landsat TM data in an alpine environment. ISPRS J. Photogram. Rem. Sens. 48(4): 17-28.

Microsoft Corporation, 1991. Microsoft FORTRAN reference. Version 5.1. Redmond, WA.

Moore, I.D., 1996. Hydrologic modeling and GIS. In: Goodchild, M.F., L.T. Steyaert, B.O. Parks, C. Johnston, D. Maidment, M. Crane, S. Glendinning (Eds.), GIS and environmental modeling: Progress and research issues. GIS World Books, Fort Collins, CO. pp 143-148.

Negahban, B. C. Fonyo, K.L. Campbell, J.W. Jones, W.G. Boggess, G. Kiker, E. Hamouda, E. Flaig, and H. Lal, 1996. A GIS-based decision support system for regional environmental planning. Ecol. Engin. 5(2+3): 391-404.

Netherlands Scientific Council for Government Policy, 1992. Ground for choices. Four perspectives for the rural areas in the European Community. Reports to the Government, No. 42. Sdu publishers, The Hague, The Netherlands.

Ostertag, C.F., 1996. Evaluacion participativa de opciones de mercado con pequenos productores de la microcuena del Rio Cabuyal. Informe final. Projecto Desarrollo Agroempresas Rurales, CIAT, Cali, Colombia.

Ostrom, E., 1990. Governing the commons. The evolution of institutions for collective action. Cambridge University Press, Cambridge, UK.

Ostrom, E., 1992. Community and the endogenous solution of commons problems. J. Theor. Pol. 4(3): 343-351.

Ostrom, E., S. Schroeder, and S. Wynne, 1993. Institutional incentives and sustainable development. Westview Press. Boulder, CO.

Ostrom, E., W.F. Lam, and M. Lee, 1994. The performance of self-governing irrigation systems in Nepal. Human Syst. Man. 13: 197-207.

Papajorgji, P., J.W. Jones, G. Hoogenboom, and J.P. Calixte, 1994. Exploring concepts for linking GIS and crop models. In: D.G. Watson, F.S. Zazueta, and T.V. Harrison (eds.), Proceedings of the 5th International Conference "Computers in Agriculture", February 6-9, Orlando, FL. pp 598-602.

Peters, N.E., 1994. Hydrologic processes. In: B. Moldan and J. Cerny (eds.). Biogeochemistry of small catchments: a tool for environmental research. John Wiley, New York. pp 207-223.

Pickering, N.B., Hansen, J.W., Jones, J.W., Wells, C.M., Chan, V.K., and Godwin, D.C., 1994. WeatherMan: A utility for managing and generating daily weather data. Agron. J. 86: 332-337.

Priestley, C.H.B. and R.J. Taylor, 1972. On the assessment of the surface heat flux and evaporation using large scale parameters. Monthly Weather Rev. 100: 81-92.

Rabbinge, R., C.A. van Diepen, J. Dijselbloem, G.H.J. de Koning, H.C. van Latesteijn, E. Woltjer, and J. van Zijl, 1994. 'Ground for Choices': a scenario study on perspectives for rural areas in the European community. In: L.O. Fresco, L. Stoorsnijder, J. Bouma, and H. van Keulen (eds.), The future of the land. Mobilising and integrating knowledge for land use options. John Wiley, New York. pp 95-121.

Rallison, R.E. and N. Miller, 1982. Past, present, and future of SCS runoff procedures. In: V.P. Singh (ed.), Rainfall-runoff relationships. Water Resources Publications, Littleton, CO. pp. 353-364.

Ramirez, R.M., 1992. Estadisticas sobre el recurso aqua en Colombia (segunda edicion). Ministerio de Agricultura y Instituto Colombiano de Hidrilogica, Bogota, Colombia.

Raper, J., D. Livingstone, 1996. High-level coupling of GIS and environmental process modeling. In: M.F. Goodchild, L.T. Steyaert, B.O. Parks, C. Johnston, D. Maidment,

M. Crane, and S. Glendinning (eds.), GIS and environmental modeling: Progress and research issues. GIS world books, Fort Collins, CO. pp 387-390

Rappoldt, C. and D.W.G. van Kraalingen, 1996. The Fortran Simulation Translator (FST) version 2.0. Introduction and reference manual. Quantitative approaches in systems analysis, No. 5. DLO-Research Institute for Agrobiology and Fertility, The C.T. de Wit Graduate School for Production Ecology, Wageningen, The Netherlands.

Raskin, P., P. Gleick, P. Kirshen, G. Pontius, and K. Strzepek, 1997. Water futures: Assessment of long-range pattern and problems. Stockholm Environment Institute, Stockholm, Sweden.

Ravnborg, H.M. and J.A. Ashby, 1996. Organizing for local-level watershed management—Lessons from Rio Cabuyal watershed, Colombia. In: CIAT Hillsides Agro-Ecosystem Program, Annual Report 1995-1996. CIAT, Colombia. pp. 131-151.

Ravnborg, H.M., J. Rubiano, and M. del Pilar Guerrero, 1996. Experiments with a stakeholder approach to watershed management: The issue of burnings in Rio Cabuyal. In: CIAT hillsides program, annual report 1994-1995. CIAT, Cali, Colombia. pp. 153-163

Renard, Y., 1991. Institutional challenges for community-based management in the Caribbean. Nat. Res. 27(4): 4-9.

Revelo, C.F., V.M. Barrero and C.A. Escobar, 1994. Estudio de detallado de suelos, Corporacion Autonoma regional de Cauca (CVC), Cali, Colombia.

Rewerts, C.C. and Engel, B.A., 1991. ANSWERS on GRASS; Integrating a watershed simulation with a GIS. ASAE paper no. 91-2621. ASAE, St. Joseph, MI.

Richards, L.A., 1931. Capillary conduction through porous mediums. Physics 1:313-318.

Ritchie, J.T., 1972. Model for predicting ET from a row crop with incomplete cover. Wat. Res. Res. 8: 1204-1213.

Ritchie, J.T., 1998. Soil water balance and plant water stress. In: G.Y. Tsuji, G. Hoogenboom, and P.K. Thornton (eds), Understanding options for agricultural production. Kluwer, Dordrecht, The Netherlands. pp 41-54.

Rhoades, R.E., 1998. Participatory watershed research and management: Where the shadow falls. Gatekeeper Series no. 81. Sustainable Agricultural and Rural Livelihoods Programme, International Institute for Environment and Development (IIED), London, UK.

Roberts, R.S. and J. Emel, 1992. Uneven development and the tragedy of the commons: Competing images for nature-society analysis. Econ. Geogr. 68(3): 249-272.

Rubiano, J.E., 1998. Hydrological impacts of land use change in tropical hillsides: the impact of changes. Master's thesis, King's College London, London, UK.

Rutter, A.J., 1967. An analysis of evapotranspiration from a stand of Scots Pine. In: W.E. Sopper and H.W. Lull (eds.), International symposium of forest hydrology. Pergamon Press, Oxford, UK. pp 403-417.

Schipper, R.A., D.M. Jansen, and J.J. Stoorvogel, 1995. Sub-regional linear programming models in land use analysis: A case study of the Neguev settlement, Costa Rica. Netherlands J. Agric. Sci. 43: 83-109.

Scholberg, J.M.S., K.J. Boote, J.W. Jones and B.L. McNeal, 1996. Adaptation of the CROPGRO model to simulate the growth of field-grown tomato. In: M.J. Kropff, P.S. Teng, P.K. Aggarwal, and B.A.M. Bouman (eds.), Applications of systems approaches at the field level. Kluwer, Dordrecht, The Netherlands. pp 135-151.

Schulze, R.E. and W.J. George, 1987. A dynamic, process-based, user-oriented model of forest effects on water yield. Hydrol. Proc. 1: 293-307

Seckler, D., D. Barker, and U. Amarasinghe, 1999. Water scarcity in the twenty-first century. Int. J. Wat. Res. Dev. 15(1): 29-42.

Seckler, D., U. Amarasinghe, D. Molden, R. de Silva, and R. Barker, 1998. World water demand and supply, 1990 to 2025: Scenarios and issues. Research report 19. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Serageldin, I., 1999. Looking ahead: water, life and environment in the twenty-first century. Int. J. Wat. Res. Dev. 15(1): 17-28.

Serageldin, I., 1998. Water in the 21st century: a dialogue. Wat. Pol. 1: 129-137

Singleton, A. and M. Taylor, 1992. Common property, collective action and community. J. Theor. Pol. 4(3): 309-324.

Srinivasan, R. and Arnold, J.G., 1994. Integration of a basin scale water quality model with GIS. Wat. Res. Bull. 30(3): 453-462.

Srinivasan, R. and B.A. Engel, 1994. A spatial decision support system for assessing agricultural nonpoint source pollution. Ground Wat. 32(3): 480-488.

Stoorvogel, J.J., R.A. Schipper, and D.M. Jansen, 1995. USTED: A methodology for quantitative analysis of land use scenarios. Netherlands J. Agric. Sci. 43: 5-18.

Swartzendruber, D., 1969. The flow of water in unsaturated soils. In: R.M. DeWiest (ed.), Flow though porous media. Academic Press, New York. pp 215-292.

Sweeting, M.M., 1973. Karst landforms. Colombia University Press, New York.

Thornton , P.K. and P.G. Jones, 1997. Towards a conceptual dynamic land-use model. In: P.S. teng, M.J. Kropff, H.F.M. ten Berge, J.B. Dent, F.P. Lansigan, and H.H. van Laar (eds.), Applications of systems approaches at the farm and regional levels, Volume 1. Kluwer, Dordrecht, The Netherlands. pp 341-356.

Tim, U. S., 1996. Coupling vadose zone models with GIS: emerging trends and potential bottlenecks. J. Env. Qual. 25: 535-544.

U.S. Army Corps of Engineers, 1991. Geographic resource analysis support system, version 4.0. User's reference manual. Construction Engineering Research Laboratory, Champaign, IL.

United Nations, 1998. World population prospects. The 1996 revision. UN Department of Economic and Social Affairs, Population Division. New York.

USDA-SCS, 1972. National engineering handbook, Section 4, Hydrology. U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS). Washington, DC.

Veldkamp, A. and L.O. Fresco, 1996a. CLUE: A conceptual model to study the conversion of land use and its effect. Ecol. Mod. 85: 253-270.

Veldkamp, A. and L.O. Fresco, 1996b. CLUE-CR: An integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecol. Mod. 91: 231-248.

Veldkamp, A. and L.O. Fresco, 1997a. Exploring land use scenarios, an alternative approach based on actual land use. Agric. Syst. 55: 1-17.

Veldkamp, A. and L.O. Fresco, 1997b. Reconstructing land use drivers and their spatial scale dependence for Costa Rica (1973 and 1984). Agric. Syst. 55: 19-43.

Verburg, P.H., G.H.J. de Koning, K. Kok, A. Veldkamp, and J. Bouma, 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecol. Mod. 116: 45-61.

Waltner-Toews, D., 1996. Ecosystem health: A framework for implementing sustainability in agriculture. BioScience 46(10): 686-689.

Wang, H.F. and Anderson, M.P., 1982. Introduction to groundwater modeling. Finite difference and finite element methods. Freeman, New York.

Warwick, J.J. and S.J. Haness, 1994. Efficacy of ARC/INFO GIS applications to hydrologic modeling. J. Wat. Res. Plan. Manage. 120(3): 366-381.

Watkins, D.W., D.C. McKinney, D.R. Maidment, and M.-D. Lin, 1996. Use of geographic information systems in groundwater flow modeling. J. Wat. Res. Plan. Manage 122(2): 88-96.

Wells, M. and K. Brandon, 1992. People and parks: Linking protected area management with local communities. The World Bank, WWF, and USAID. Washington, DC.

## BIOGRAPHICAL SKETCH

Joseph (Joep) Carlos Luijten was born on August 14, 1969 in Sittard, The Netherlands. He grew up on a farm in a small nearby village. After receiving his "Voortgezet Wetenschappelijk Onderwijs (VWO)" high school diploma in July 1988, he was one of few students to start a new M.Sc. program in agricultural systems science at the Wageningen Agricultural University, Wageningen, The Netherlands. He specialized in the areas of systems science, computer science, computer simulation, and crop growth modeling. He wrote one thesis in computer science and another one in agricultural engineering and physics. He spent his first practical period at the Institute of Biosystems Engineering, Federal Agricultural Research Center, Braunschweig, Germany (January-May 1993), and the second at the Crop Systems Modeling Laboratory in the Agricultural Engineering Department of the University of Florida, Gainesville, Florida (September 1993-February 1994). In June 1994, he graduated *cum laude* in agricultural systems science. After graduation, he worked for one year as a research associate at the DLO-Research Institute for Agrobiology and Soil Fertility (AB-DLO), Wageningen, The Netherlands. In July 1995, he returned to the University of Florida to pursue a Ph.D. degree in Agricultural and Biological Engineering. He conducted the dissertation research in cooperation with the International Center for Tropical Agriculture (CIAT), Cali, Colombia. He received his Ph.D degree in December 1999.