WETLAND AND WATER DYNAMICS IN SMALL TROPICAL HEADWATER CATCHMENTS OF THE ANDES

by

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Abstract

Small communities of the Colombian Andes have a large dependency on ecosystems for their water supply. Colombia has a policy of equitable access to water, but as a result of current institutional arrangements, rural communities have limited access to resources for the improvement of water infrastructure. A case study in the headwater region of the Barbas river catchment, examined the ecological and hydrological dynamics of providing a reliable flow of water to the community of Filandia, population 15,000. The catchment has numerous wetlands that are believed to be an important regulator of water flow especially in supplying baseflow during the dry season. Three wetlands were selected for detailed instrumentation and monitoring and were found to have different hydrological regimes but none of them contributed significant volumes to low flows during the dry season. The presence of an open water surface within a wetland, and a surface outflow, together with wetland size were found to be critical factors for the maintenance of low flows and the water yield of wetlands in relation to their host catchment. Antecedent precipitation conditions determined the discharge coefficient of wetlands, and lag time between peak in rainfall and discharge was influenced by wetland size and precipitation intensity. On the basis of isotopic signals from rain and wetland outflows, wetlands were found to prolong the response time of water in their catchments. Soils are andic with a low storage-discharge coefficient that differ depending on land use. Differences in soil water dynamics at the catchment scale were related to streamflow, and indicate that forests with the largest capacity to store and release water, reduced the fluctuation of baseflow in comparison with grasslands. The isotope analysis revealed a higher runoff coefficient for grasslands. Based on yield analysis, discharge coefficients, FDC, and two approaches of water isotope composition analysis, it was shown that although forests compete for water during the dry season, their soils contribute to sustaining baseflows. Results suggest that to maintain a regular and reliable flow of water for local rural communities, conservation of these upland headwaters is important, and that additional small scale storage structures are necessary.

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LIST OF ABBREVIATIONS

B1 – Bolillos 1
B2 – Bolillos 2
BB – Barro Blanco
B1S – Bolillos 1 stream
B2S – Bolillos 2 stream
BBS – Barro Blanco stream
B1W – Bolillos 1 wetland
B2W – Bolillos 2 wetland
BBW – Barro Blanco wetland
CARs – Corporaciones Autónomas Regionales (Regional Environmental Entities)
CRA – Comisión de Regulación de Agua Potable y Saneamiento Básico (Commission for Regulation on Water and Sanitation)
CONPES – Consejo Regional de Política Económica y Social (Regional Council for Economic and Social Policy)
CRQ – Corporación Autónoma Regional del Quindío (Regional Environmental Office for Quindío)
DC – Discharge coefficient
ESAQUIN – Empresa de Servicios de Agua y Alcantarillado del Quindío (Water and Sanitation Enterprise of Quindío)
FDC – Flow duration curve
IAEA – International Atomic Energy Agency
IDEAM – Instituto Nacional de Meteorología, Hidrología y Recursos Naturales (National Institute for Meteorology, Hydrology and natural Resources)
IGAC – Instituto Geográfico Agustín Codazzi (Geographical Institute Agustín Codazzi)
MRT – Mean Response Time
MTT – Mean Transit Time
MVADT – Ministerio de Vivienda, Ambiente y Desarrollo Territorial (Ministry of Environment, Housing and Territorial Development)
PET – Potential Evapotranspiration
RC – Runoff coefficient
RMSE – Root Mean Square Error
RR – Acueducto Rural Regional (Regional Rural Water Distributor)
SSDP – Superintendencia de Servicios Públicos Domiciliarios (Superintendency for Residential Public Services)
TTD – Transit Time Distribution
UNDP – United Nations Development Program
UNICEF – United Nations Children’s Fund
WHO – World Health Organization

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Co-authorship statement

All four main chapters of this thesis were prepared as stand-alone manuscripts for submission to peer-reviewed journals. I am the senior author of all these chapters. I was responsible for the conceptualization, design, data collection, data analyses and writing of these chapters. Specific contributions by my supervisor and co-authors are outlined below.

Chapter 2

This chapter will be co-authored with professor Sandra Brown, who contributed to the design of the study of the water use data. She collected and analyzed the water samples for sediment content, and was involved in the overall design and implementation of the research project.

Chapter 3

This chapter will be co-authored with professor Les Lavkulich and professor Sandra Brown. Professor Lavkulich contributed to the integration of the research components of the chapter, and participated in the design of the monitoring program of wetland characteristics. Professor Brown supported the monitoring program, and provided suggests for the analysis.

Chapter 4

This chapter will be co-authored with my supervisor professor Hans Schreier, who contributed to the design of the hydrology monitoring program at the catchment and wetland scales; and provided guidance for the statistical analysis, interpretation of results and integration.

Chapter 5

This chapter will be co-authored with professor Markus Weiler, who participated in the design of the isotope sampling program, designed the modified version of TRANSEP, the model used for data analysis, and guided the interpretation of results.

1. Introduction

Water resource management is now of global concern due to increasing human population, increasing demand by the agricultural and manufacturing sectors and the expansion of cities, combined with the effects of climate change on the hydrological cycle. These factors have been linked to water shortages, degradation of water quality and the destruction of aquatic ecosystems (UNDP, 2008). Even in regions where precipitation is high, water can be a limited resource, if conditions such as high variability in temporal or spatial distribution of precipitation are present, or if the institutional arrangements do not respond to the combination of high variability of local climatic and environmental conditions and high demand.

Colombia is considered a water rich country, yet it faces recurrent water scarcity. It is estimated that out of 44 million ha of its territory, 2.7 million ha correspond to lakes, wetlands, reservoirs and bogs; it has more than 24,000 km of rivers and 742,000 micro-catchments (IDEAM, 2000). Urban development, agricultural and industrial activities have been located in regions that are vulnerable to water shortages which has generated excessive pressure on water resources and has started to cause significant water availability problems particularly during extremely dry periods and during periods of the warm oscillation of the Pacific Ocean (El Niño). Eighty per cent of the municipalities of Colombia obtain their water from small creeks and streams that are located in catchments with limited buffer capacity and high vulnerability, which does not contribute to a reliable supply of water (IDEAM, 2000).

According to the World Health Organization Joint Monitoring Program for Water and Sanitation, in 2004, 93% of the total population of Colombia (44.9 million) had access to an improved source[1] of water. The rural population, which accounts for about 23% of the national total (10.3 million), has the lowest availability, with only 71% having access to safe water and only 51% with household connections (WHO-UNICEF, 2006).

The National Water Study published by IDEAM in 2000, reported that 50% of the urban population of Colombia is prone to water shortages in a normal year, and 80% of the population in a dry year. In fact, the average duration of daily water service at the national level was 19.8 hours in 2003. In the four largest cities of the country, service is continuous. Nevertheless, rationing of water and interrupted sanitation are ordinary incidents in small towns and rural areas (Fernandez, 2004). IDEAM's forecast for the years 2015 and 2025 is that if water management is not improved, 66% and 69% of the population respectively could be under high risk of water shortages during a dry year. Despite the efforts made by recent governments to provide the regulatory framework and policies to improve water services in the country, two important aspects have been overlooked: 1) the large temporal and spatial variability

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[1] According to the World Health Organization – WHO and the United Nations Children's Fund - UNICEF access to water supply services is defined as the availability of at least 20 liters per person per day from an improved source within one km of the user's dwelling. Improved water sources include household connections, public standpipes, boreholes, protected dug wells, protected springs and rainwater collection (Joint Monitoring Program, 2006).

of precipitation and the local variability of ecosystems' buffer capacity to store-supply water; and 2) the inequity in the distribution of resources for infrastructure development.

Water scarcity is the result of either low baseflows, or stormflows carrying high concentration of sediments that produce water that is difficult to treat. Water shortages in an area of abundant precipitation raise questions about the conditions of water sources (e.g. catchment ecosystems), and about how water governance issues are being addressed.

The water cycle in mountain regions of the world is a complex system that is not fully understood particularly in tropical mountains where the interaction of local topographic and environmental conditions, orographic effects, and large scale climate-forcing mechanisms interact creating unique hydrologic conditions that are extremely sensitive to location (Poveda, et al., 2005). The relative abundance of water resources in Colombia has minimized the concern about the importance of the high variability both in spatial and temporal scales, and therefore water laws and regulations do not incorporate the natural variability of the hydrological cycle and institutions have been developed without consideration of cyclical or permanent reductions in water availability, or increases in demand.

Knowledge about the capacity of headwater ecosystems is important for small municipalities and water providers, in order to understand the processes that take place at their water source regions, recognize the limitations and vulnerabilities and initiate a dialog with policy makers and the community to design management plans that incorporate the natural variability of the hydrological cycle and to consider the factors that have an influence on water availability both during the dry and the rainy season.

This research project responds to the need to generate knowledge about the hydrological behavior of the headwater catchments, in the context of water allocation, water distribution and water use. The study was conducted in the municipality of Filandia, a municipality of 15,000 people located in the central branch of the Colombian Andes (Figure 1-1), where water scarcity is recurrently an issue in the dry season. This is also a region that because of the presence of wetlands is perceived by water users downstream as a major source of their water.

1.1. Objectives

1. To provide a context to the importance of headwater catchments and their water holding capacity for the provision of water for small communities in the mountains, from the perspective of the institutions that govern water in Colombia.

2. To test the hypothesis that wetlands located in the headwater catchments are a major contributor to water availability for water providers in the dry season and the amelioration of stormflows.

3. To quantify the effects of the differences in land use over the hydrological response of small headwater catchments, including the effect of wetlands on their host catchments.

4. To quantify the effects of wetlands and forests on the hydrograph of catchments and the transit time of water using water isotopes as tracers.

1.2. Structure of the thesis

After the introductory chapter, the thesis starts by asking how water is allocated, distributed and used in Filandia, and how this compares with the water that is available throughout the year. The second chapter provides an overview of the regulatory framework for water allocation and distribution in Colombia and compares water use and water availability for Filandia, highlighting the larger decrease in water use by the particular groups during times of water shortages. The goal of the second chapter is to provide an analysis of the water provision services, the regulatory framework on which the service is based; and a comparison between water use and water availability in Filandia. This analysis establishes a baseline for the need to understand the hydrological behavior of the headwater catchments.

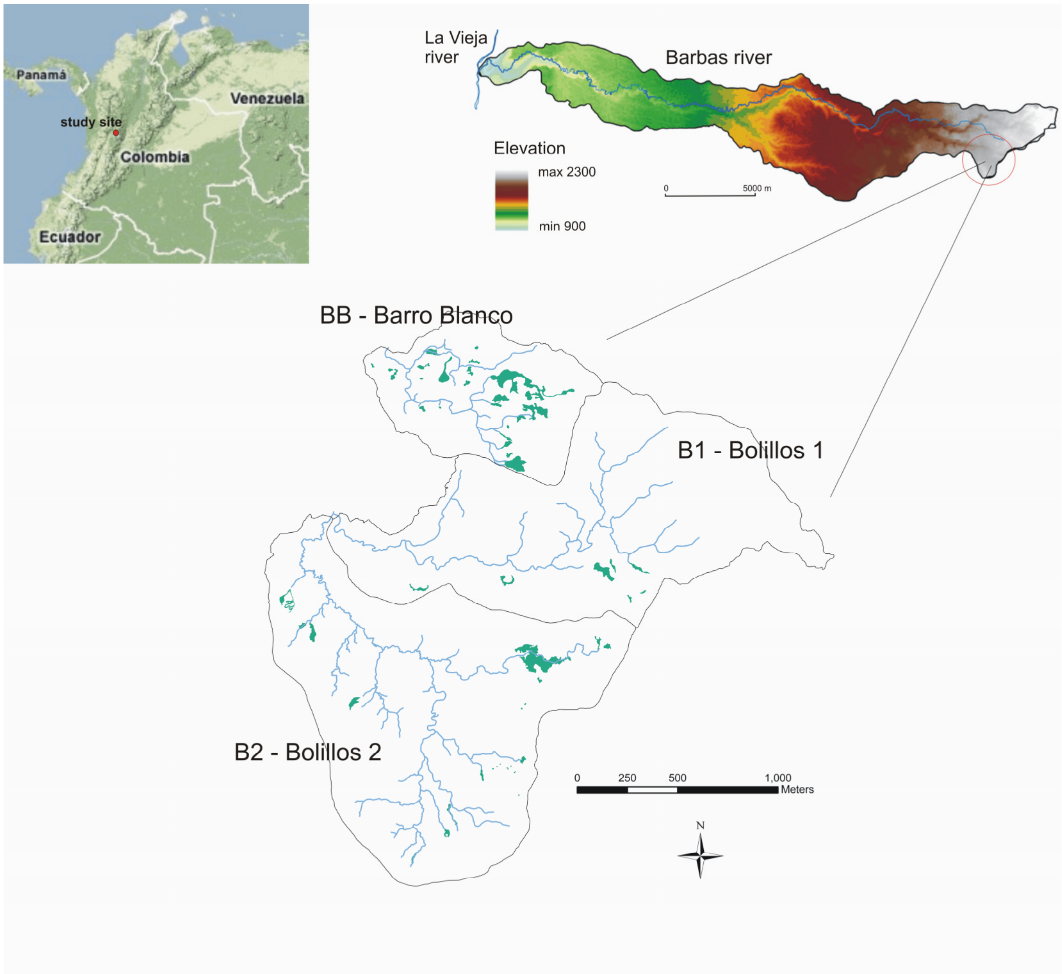

Figure 1-1 - Location of study site and the three small headwater catchments compared. The detailed map shows the wetlands found in each of the three catchments.

Given the local general belief that headwater catchments are the major water source and that resources for infrastructure maintenance and improvement are scarce, questions are formulated about the characteristics of the ecosystems that affect water regulation, particularly in times of low precipitation. The local community and water providers require evidence of the benefits of conservation measures to help them support their attempts for the acquisition of the headwater catchments.

These questions are addressed in the following three chapters. Chapter three provides an analysis of the hydrological behavior of wetlands. Placed in the broader context of the ongoing debate about the role of wetlands as water quantity regulators, this component of the study provides a characterization of the wetlands located in the study site and is based on a detailed monitoring program of three wetlands. This analysis provides an assessment of the role of wetlands in the maintenance of dry season flows and the attenuation of storm events.

Chapter four is a comparative analysis of the three small neighboring headwater catchments that constitute the water source for the municipality of Filandia. These headwater catchments called Bolillos 1 (B1), Bolillos 2 (B2) and Barro Blanco (BB) are shown in Figure 1-1. These streams flow into the Barbas river which in turn flows into the La Vieja River. Given their similar geology, topography, and climatic regime, differences in land use are the major factor determining the hydrological behavior of the three headwater catchments. The analysis of water holding capacity of soils in relation to the hydrological cycle provides a starting point for the understanding of the seasonal distribution of flows. The relatively poor capacity of soils to release water from these catchments make the effects of land use on stream discharge even more important for the provision of water for downstream users.

Chapter five explains differences in the hydrological behavior of wetlands and catchments making use of environmental tracers. The differences in mean response and transit time of water in catchments, runoff coefficients and the proportion of discharge that comes from pre-event water, corroborate the findings of the hydrological study of wetlands and catchments and provide additional information about the differences in water storage capacity and water flow regulation produced by differences in land use and management practices. The uniqueness of this research proceeds from the comparison of six geographical units during the same period of time, including five storms events.

The final chapter of summary and synthesis focuses on the question of how the scientific results described in previous chapters inform decision making for dealing with water scarcity and address equitable access to water. The goal is to make a contribution from the scientific perspective, to an equitable water supply system for small municipalities and rural communities.

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2. Dealing with water scarcity in humid headwater catchments of Colombia[1]

2.1. Introduction

Water scarcity in an area with an average annual precipitation of near 3,000 mm raises questions about possible causes. Explanations may be related to biophysical phenomena such as climate and land use change, as well as infrastructural or institutional causes that can limit water access to users. When water scarcity is unequally distributed among users, the causes can be linked to biophysical processes but will be ultimately related to institutional arrangements (Gleick, 2000).

The laws and regulations on tariffs, concessions, infrastructure and the protection of water sources in Colombia, have the intention of providing equal access to water to all the population of Colombia, as a constitutional right. However, the fragmentation of the system, combined with some pervasive incentives, lack of enforcement, disregard for particular traits of ecosystems regarding water regulation capacity, the spatial and temporal variability of precipitation and the vulnerability of ecosystems to climate and land use change, can lead to inequitable access to water by disadvantaged groups.

Filandia has a population of approximately 15,000 people, 44% living in the urban area that occupies less than 1% of the 10,940 ha of the municipality (CRQ, 2003). Filandia's economy was based on coffee production for several decades. In the 1990s, the fall of international coffee prices coincided with a widespread infestation of the coffee borer beetle. During this period, many farms abandoned coffee production and replaced it with pastures for livestock under intensive management systems. In 2002 land ownership was concentrated in small landholdings: 35% of farms had areas of less than one ha, 30% had areas between one and three ha and 13% of farms had areas between three and five ha (IGAC, 2002).

The water source for the entire municipality of Filandia is from three small catchments occupied by five productive farms dedicated to cattle rearing for milk production, cattle and bullfighting bulls. These farms exert different degrees of pressure on the natural resources including forests, wetlands, soils and water, through their land management practices.

The objective of this chapter is to provide a baseline from the perspective of regulations and the evolution of the water sector in Colombia that can contribute to explain why Filandia, a small community located in a mountain tropical humid area, is subject to water scarcity and why this water scarcity is unequally distributed.

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[1] A version of this chapter will be submitted for publication.
Roa-García, C., Brown, S. Dealing with water scarcity in humid headwater catchments of Colombia

2.2. Methods

The institutional framework for the access, protection and distribution of water was synthesized from various sources that included the several Colombian laws (Republica de Colombia, 2009), that since 1974 deal with water as a public resource, and existing literature that analyzes the issues of the water sector in Colombia.

Water use data and number of users by income level were provided by the two water purveyors of Filandia, Empresa Sanitaria del Quindío – ESAQUIN, and Rural Regional -RR. Compilation and analysis of meter data was done for years 2004 and 2006, a dry and a wet year respectively, to provide a comparison of water use for the different income level groups.

The calculation of the water scarcity index was based on the methodology developed by the National Institute for Hydrology and Meteorology - IDEAM (2000) for Colombian rivers and communities. This index is based on water use data, stream discharge, minimum flows and temporal variation in stream flow. Details of the method are provided in Appendix 1.

Information about the mechanisms people use during periods of water shortages was obtained through key informant survey of eight rural water users conducted during the dry season of 2006. The technical operator of the RR water provider suggested farms to visit from different locations in the area of service coverage representative of the local conditions; and the farm owner or manager was interviewed.

Precipitation data since 1971 was provided by the regional environmental authority – CRQ and was used to compare a long term monthly average with the monthly precipitation of recent years, particularly 2004 and 2006.

Discharge data for the three streams that constitute the water source for the two water purveyors of Filandia were collected through this research project and the methods are fully described in Chapter four.

2.3. Regulatory framework for the provision of water services

The provision of water and sanitation in Colombia was centralized until the mid 1980's, when there were only a few municipal enterprises in the largest cities and large national enterprises provided service in other urban centers, all under the control of the Institute for Municipal Development. This Institute was eliminated in the mid eighties and the enterprises were transferred to the municipalities and provinces, and the system became decentralized and divided into a large number of small organizations.

In Colombia the national government develops the policies and regulatory framework for the provision of water, but it is the municipalities that are responsible for ensuring equitable access to water for all. Large municipalities with a large tax base, and water enterprises providing water service to a balanced mix of high-income and low-income water users, are better prepared to invest in infrastructure and the protection of water sources. Small and poorer municipalities, with less revenue from taxes and where most of the water users are domestic of lower income and small agribusinesses, have less resources to invest in the improvement of water provision. Small municipalities also receive lower financial transfers from the national government and have less opportunities to access other sources of funding (Fernandez, 2004). As a consequence, these municipalities are more dependent on natural ecosystems for the provision of a reliable source of water and are more vulnerable to fluctuations in precipitation patterns, since these smaller municipalities lack the capacity to build reservoirs and access more distant water sources.

Tariffs for water provision are structured to subsidize the service to the lower income groups of the population, and to provide incentives for efficient use and conservation measures. But the small scale of most of rural water providers and their provision of water to mostly lower income communities does not facilitate reaching economies of scale or having the financial resources for infrastructure development. Consequently these systems rely on the regulation capacity of ecosystems to provide water of good quantity and quality for distribution (Fernandez, 2004). In the mid 1980's, when the provision of water services was decentralized, responsibility for the service was transferred to the municipalities, but the central government kept – by constitution and law – the control and regulation of public utilities, the medium and long term planning of the sector and the definition of environmental policy.

The national government sets the policy for the provision of water services and exerts regulation and control of infrastructure development and tariffs. The Vice-Ministry of Water and Sanitation, created in October 2006 within the Ministry of Environment, Housing and Territorial Development - MVADT is in charge of setting sector policy. This ministry also sets the policy for the use of natural resources. Regulation is the responsibility of two separate institutions at the national level: the Comisión de Regulación de Agua Potable y Saneamiento Básico – Commission for Regulation on Water and Sanitation - (CRA) which defines criteria for efficient service provision and sets the rules for tariff revision; and the Superintendencia de Servicios Públicos Domiciliarios (SSPD) or Superintendency for Residential Public Services, a multi-sector regulatory organization in charge of enforcing the application of these regulations.

At the regional scale the Consejo Regional de Política Económica y Social – CONPES or Regional Council for Economic and Social Policy and the departments (provinces) have the responsibility of articulating the national policy at the municipal scale, and to provide technical assistance to service providers in relation to the design and construction of infrastructure, the operation and administration of the system, control of losses and commercial issues. Additionally at the regional scale there are 36 Corporaciones Autónomas Regionales – CARs or Regional Environmental Entities, which are environmental authorities, entitled to grant water concessions, water licenses, approval of environment management plans and to control and monitor the quality and quantity of waste water disposal.

At the local scale, the 1,091 municipalities are responsible for providing water services, investments in infrastructure and have the autonomy to choose the legal structure of the service provider that best suits their needs. The plans are responsible for the design and implementation of an investment plan for water and sanitation for urban and rural areas. The service provider enterprises are responsible for quality of the service up to where the pipes enter the household or to the point where the water meters are installed (WHO, et al., 2000). The boards of these enterprises (public or private) are responsible for setting tariffs, subject to the national regulation.

A description of the water sector and the roles of each institution for the provision of equal access to water for the population of Colombia is summarized in Table 2-1.

Table 2-1 - Institutional responsibilities for the provision of water services

Level	Institution	Roles
National	Vice-Ministry of Water and Sanitation - Ministry of Environment, Housing and Territorial Development	• Policy for the provision of water services and exerts regulation and control of infrastructure development and tariffs • Policy for the use of natural resources
	Commission for Regulation on Water and Sanitation (CRA)	• Definition of criteria for efficient service provision and rules for tariff revision
	Superintendency for Residential Public Services	• Controlling the application of these regulations
Regional	Regional Council for Economic and Social Policy - CONPES	• Articulation of national policy at the municipal scale • Provide technical assistance to service providers in relation to the design and construction of infrastructure, the operation and administration of the system, control of losses and commercial issues
	Regional Environmental Entities (CARs)	• Grant water concessions and water licenses • Approval of environment management plans • Control and monitoring of the quality and quantity of waste water disposal
Local	Municipalities	• Provide water services • Investments in infrastructure • Choose the legal structure of the service provider that best suits their needs • Design and implementation of an investment plan for water and sanitation for urban and rural areas
	Enterprises	• Provide quality water services up to where the pipes enter the household or to the point where the water meters are installed • Setting tariffs, subject to the national regulation

In 2007, the CONPES designed Planes Departamentales de Agua – Regional Water Plans which constitute a national strategy to improve coverage of water and sanitation services and improve the quality of the service. They are intended to achieve inter-institutional coordination among the different actors of the water sector at all scales, modernize water enterprises across the country, reach economies of scale in the provision of the service through regional schemes, articulate the various sources of funding and access to credit, improve control and compliance with norms, and promote regional investment plans for the short, medium and long terms (CONPES, 2007). Each region has a plan that operates through a trust. Water providers apply with their specific investment projects to the plan board.

It is estimated that service is provided by more than 1,500 water and sanitation providers in urban areas and more than 12,000 community organizations in rural areas. However, 70% of the urban and more than 55% of the total population is served by 40 enterprises in 70 municipalities (Fernandez, 2004). In terms of private service provision, over 90 municipalities have granted concessions to private enterprises for water service provision. The providers in smaller municipalities and rural areas cannot realize economies of scale and do not have the needed infrastructure capacity or personnel to store, treat and distribute water and improve and maintain infrastructure. The national government has provided incentives to merge or takeover small providers by larger ones through tax breaks. However, small municipalities are afraid of loosing control over water resources, the larger companies have not found the tax rebates attractive enough and perceive an unstable environment (Fernandez, 2004), since water tariffs are used as a political instrument (Gomez, 2009, personal communication) as evidenced by the fact that the CRA has announced the intention to reduce tariffs, which does not promote investment in or expansion of infrastructure.

2.3.1. Tariffs

The current rate structure charges a fixed rate for administrative costs and a variable rate for the amount of water consumed. Large providers use micro-meters in 80% of their connections that are paid for by the consumer, except in locations where water quality or the temporary nature of the settlement or network do not make the installation feasible. The cost of a micro-meter in Colombia is between US$30 and US$40. The average water bill paid monthly by each domestic household in 2006 was US$6.8.

The base water tariff is calculated on the basis of economic costs and based on a methodology defined at the national level by CRA (Law 287 of 2004) that includes operational and administrative costs, investment plans and estimates for non-revenue water (technical losses and illegal connections). Therefore, tariffs in different municipalities do not differ due to local government's decisions to control tariff costs, but only reflect different costs of the services (SSPD, 2007). From 1990 to 2001, tariffs for medium size to large water providers have more than doubled from US$0.32 / m^3 to US$0.81 / m^3, an increase of 152%. The average tariff for a medium size water provider (100,000 – 500,000 users) was US$0.42 / m^3 in 2001 and for a large water provider (> 500,000 users) US$0.85 / m^3 (Fernández, 2004).

Tariffs are adjusted by law according to socio-economic levels, which is linked to the quality of houses and surroundings. Each municipality determines the percentages of adjustment for each socio-economic level according to the maximum subsidy allowed by law which was initially set for 50% for income level 1, 40% for income level 2 and 15% for income level 3 (Law 142 of 1994). In order to cover these subsidies, water users of income levels 5 and 6 and non-residential users can be charged up to 20% higher than the calculated cost. However, given that the large majority of the population are at income levels 1-3 (72% average for seven larger cities) the system remains in deficit and the Law has been modified to allow tariffs higher than 20% for higher income levels (Law 632 of 2000) and to allow subsidies of up to 70% for income level 1 (Law 812 of 2003). The subsidy scheme only works where the number of users paying over charged tariffs generates enough income to cover the subsidies for users in lower income groups (e.g. larger cities). In smaller municipalities, which have a higher proportion of low income population (socio-economic groups 1 to 3) the deficit must be covered through other fiscal resources. In addition, in 1993 the CRA established 20 m^3/household/month as the minimum water volume to be covered by the base tariff. Volumes above this level are charged at incremental rates per m^3 consumed. Given that only a small percentage of households across the country consume this much water per month, this volume can be considered excessive, and does not stimulate additional water saving behavior nor does it generate extra income for water providers. However, overall tariffs may have already had an effect on reducing water use. According to Fernandez (2004) an increase in tariffs in place since 1996, and recent improvements in distribution technology resulted in lower water use as illustrated in Table 2-2.

Table 2-2 - Water use per connection per month in six major cities in Colombia in cubic meters (Fernandez, 2004)

Income level	1996	1997	1998	1999	2000	2001	change
1	22.9	21.4	19.4	18.0	16.9	16.0	-22.0%
2	24.9	25.6	22.9	21.3	19.9	18.5	-28.0%
3	23.6	25.4	23.4	21.9	20.6	18.6	-26.0%
4	23.8	25.3	23.7	22.6	21.5	19.8	-19.6%
5	28.0	28.8	27.3	26.2	24.2	22.8	-19.9%
6	34.7	34.3	31.7	29.7	28.7	27.7	-18.8%

2.3.2. Infrastructure

The level of non-revenue water (losses due to illegal connections or leakages) was estimated to be 40% in 2001 for large water providers. In 2006 it was estimated to be 49% for all the water suppliers reporting to the national control agency (SSPD, 2007). This level is higher than the Latin American average (approximately 40%) and the regulatory goal of 30%. In the largest cities of the country, levels of non-revenue water are below the national average (40% in Bogotá, 35% in Medellín and 39% in Cali).

Building and updating infrastructure is self funded by water providers, by national and provincial funds and by resources from the regional environmental authorities. According to the Fernandez (2004), in 2004 the available sources of funding for the sector amounted to around US$410 million as given in Table 2-3.

Table 2-3 - Available funding for the water sector in 2004 (Fernandez, 2004)

Source	Share
Water enterprises	26%
State funding (Law 715 – SGP)	61%
CARs	
Property tax and electricity utilities	10%
Waste water discharge fee	2%
National Resource Extraction Fund (Fondo Nacional de Regalías)	1%

State funding for water and sanitation is dictated by Law 715 of 2001 and although a large portion of the funds transferred to municipalities from the national government is destined to be invested in water and sanitation infrastructure, the limited control that the national government exercises over these resources does not ensure that all the transferred funds are invested in water and sanitation. Through this Law, municipalities also receive other unrestricted resources that are rarely invested in water and sanitation. Municipalities rarely allocate their own resources for this type of infrastructure (Fernandez, 2004). Small water providers have a limited capacity to access municipal resources and there is no institution or program at the national level which offers technical assistance to the 12,000 rural community organizations of which only 21% are considered able to carry out maintenance, 10% are regarded as commercially able to operate the service, 8% had conducted a study of costs and tariffs, 32% issued bills and only 10% used metering (MAVDT, 2005).

The inventory of water and sanitation infrastructure completed in 1996 by the national government, collected information about 1,318 service providers out of the estimated 13,500 total providers in the country. According to the inventory, there are 1,000 tanks with a total storage capacity of 1.5 million m^3 (Fernandez, 2004). The shortcomings found in the infrastructure including connections, treatment plants and sanitation have made water storage a less critical issue. The fact that water, in comparison with other utilities such as energy, gas and telecommunications can be stored by users is considered an advantage for the sector so that public investment in storage by providers is not required. However this does not take into account the risks associated with the variability in water availability due to the impacts of land use on the water regulation capacity of headwater catchments and the impact of more severe dry spells associated with climate variability. One consequence of the lack of storage particularly for small water providers is that storage facilities are often built by individual users who can afford them, and who during the times of water shortages, store water at the expense of poorer users who are left without the resource (key informant survey, 2006).

Through the Water Provincial Plans, the national government intends to provide the financial structure, support in implementation and follow up to municipalities in their responsibility of increasing service coverage, and making good use of resources assigned for water, sanitation and garbage management. The Plans are to be managed by a committee formed by the provincial governor, the mayors, one representative from the Ministry of Environment, Housing and Territorial Development, water providers, CARs and other local entities.

2.3.3. Concessions

The CARs are responsible for granting concessions or permits for the use and distribution of water by water providers. According to Law 2811 of 1974, permits are granted for the temporal use of the resource and can be granted for a maximum of 10 years. Concessions may be granted for longer periods and the duration depends on the economic and social returns of the use of the resource.

Given the number of streams under the jurisdiction of CARs, a detailed assessment of water flow fluctuations is not considered feasible and usually concessions are granted based on a few flow measurements. The hydrology and natural resource research institute – IDEAM, has proposed the use of a water scarcity index as a mechanism to assess the vulnerability of communities to suffer from water shortages on an annual basis. For systems characterized by high inter annual variability, the assessment of water availability based on the mode of flow measurements does not portray the variability in stream discharge that is seen on a monthly or weekly basis. This points to the need to integrate information about seasonal fluctuations of water flows, with the existing infrastructure for water storage and the mechanisms of granting concessions to water providers.

Considering the fact that 60% of the Colombian population is located in the Andean region where precipitation is highly variable, it would be advisable that the regulation about water concessions considered the natural variability of water availability throughout the year. Additionally CARs should grant concessions based on the natural limits of individual streams. Concessions are granted on a first-come-first-served basis and it is required in times of scarcity, that water be distributed proportionally among the grantees.

2.3.4. Water source protection

Laws and regulations have been written for the protection of the ecosystems on which the provision of water for water providers depends, but limited enforcement mechanisms are in place (Vargas, C., Gómez, O., personal communications). Law 99 of 1993 which created the Ministry of Environment and structured the public sector in charge of management and conservation of natural resources, states that municipalities are required to use, over a period of 15 years, a percentage no less than 1% of their annual income to acquire strategic areas for the provision of water. The management of these areas should be undertaken collectively by the municipality, and the corresponding CAR, with the optional participation of civil society.

Major municipalities have acquired large areas of land in headwater regions that constitute their water sources by using their own funds and also central government funding. The regulation about the acquisition of strategic land for the provision of water has not been enforced and most medium to small size municipalities have not invested any funds in the acquisition of land (Morales, 2009, Gomez, 2009 Vargas, 2008, personal communications).

For some municipalities like Filandia, the land in the headwaters has a high commercial value because of its location at mid elevation, which makes it productive and well connected through roads. This has made it more difficult to acquire this land for water source protection. Another limitation for small municipalities with water sources located in mid-elevation micro-catchments is that the national government does not recognize small wetlands, and therefore does not facilitate their designation as protected areas or their acquisition for water provision purposes. In contrast, some of the major cities such as Bogotá and Medellín have acquired their water source areas and have designated them as ecological reserves.

2.4. Water use and availability in Filandia

The municipality of Filandia is served by two water providers: ESAQUIN serving the urban area and Rural Regional – RR serving the rural area. ESAQUIN is a regional water provider serving seven municipalities. For Filandia it has a concession for 32 liters per second from Bolillos Creek (downstream of the confluence of Bolillos 1 and 2 as shown in Figure 1-1) and was serving 1,961 connections by the end of 2007. The distribution network is 16 km long, built in 1940 and has been gradually modernized to replace the original asbestos-cement pipe. RR is a local water provider with a concession of 7 liters per second from the Bolillos creek; RR also takes water from Barro Blanco creek but has no concession over this water. RR serves 376 connections through a distribution network of 30 km built in 1978. According to the information provided by the water providers, 72% of ESAQUIN's connections belong to socio-economic levels 1 and 2 which are the lowest on the scale from 1 to 6; and 76% of RR's connections are in these categories (Table 2-4). This implies that tariffs are low and the water providers have limited resources to improve infrastructure. There is no population in Filandia in income levels 5 and 6; group 7 is used for public institutions and group 8 includes commercial or industrial users.

2.4.1. Water use

As in most small agricultural communities, water use in Filandia is higher in the rural areas where water used for agricultural activities is of similar magnitude or larger than for domestic use. This is illustrated in Tables 2-5 to 2-8 which highlight the demand of the rural sector for agricultural activities.

Water use in the rural regions in both 2004 and 2006 (Tables 2-6 and 2-8) are significantly higher for all income levels than the corresponding use in the urbanized part of the watershed (Tables 2-5 and 2-7). Average water use in the urban area was 13.6 m^3 / connection in 2006, compared to 31.5 m^3 / connection in the rural area. These figures are comparable with the water use amounts in other rural areas of Colombia with predominant small land holdings (Roa, 2005).

For RR (rural users) water use for 2006 (Table 2-8) was lower than in 2004 (Table 2-6) at all socio-economic levels despite 2006 being a "normal" year in terms of precipitation and 2004 being a dry year (see Figure 2-3). It is also clear that the higher the income level, the higher the water used per connection.

The number of water users in income level 4 has been less than eight in the last seven years in the urban area of Filandia but there are more than 100 in the rural area (Table 2-4). The urban water use per connection in Filandia (Table 2-6 and 2-8) is below the average for the major cities in Colombia (Table 2-2) except for socio-economic level 4. However due to the small number of urban users of socio-economic level 4 in Filandia, the water use by this income group is not representative.

During the dry year of 2004, the only domestic group that increased water use was income level 4 in the urban area (Table 2-5), and group 7, which corresponds to the public sector. Both water providers were forced to introduce water rationing during the driest months of the year; providers cut service to specific zones on rotational basis and stoppages were typically half a day in the urban area and one whole day in the rural area. During the driest month (August) of 2004 water use in the rural areas dropped a higher percentage than in the urban areas for all income brackets (Table 2-5 vs. Table 2-6). This is likely the consequence of the fact that the smaller water provider (RR) has its water intake below the water intake of ESAQUIN and has a very limited storage capacity.

In 2004, the socio-economic groups 1 to 3 in the rural area (RR) decreased water use proportionally to their annual consumption (Table 2-6). Group 4 also decreased water use but in a smaller percentage than group 3. During the wetter year of 2006, when rationing of water was also put in place, only groups 1 and 2 experienced a decrease in water use (Table 2-6). The percentage of water use reduction in the urban area is higher in the lower socio-economic levels in 2004 (Table 2-4). In the rural areas the water use reduction is the highest for socio-economic levels 3 and 4 (Table 2-5), which is related to the size of the farm and level of the productive activity.

Table 2-4 - Number of connections of the two water providers by the end of 2006

	Number of connections			
income level	ESAQUIN	%	RR	%
1	406	21%	121	22%
2	992	50%	177	33%
3	478	24%	119	22%
4	8	0%	125	23%
7	31	2%	0	0%
8	54	3%	0	0%
Total	1,969	100%	542	100%

Income level or socio-economic levels 1 to 4 correspond to households. Socio-economic level 7 corresponds to public sector and socio-economic level 8 corresponds to commercial/industrial sector.

During a dry year like 2004, water scarcity is extended to all income levels, particularly to those with larger agricultural activities.

Table 2-5 - Water use per connection for ESAQUIN in 2004

	Monthly average 2004 - m3		
Income level	Whole year	August	% difference
1	14.9	13.7	-8%
2	13.4	13.0	-3%
3	16.7	16.3	-3%
4	26.8	30.6	14%
7	62.2	68.1	10%
8	24.4	22.5	-8%

Table 2-6 - Water use per connection for RR in 2004

	Monthly average 2004 - m^3		
Income level	Whole year	August	% difference
1	20.2	18.1	-10%
2	21.6	19.0	-12%
3	40.7	31.9	-22%
4	69.3	59.9	-14%

Table 2-7 - Water use per connection for ESAQUIN in 2006

	Monthly average 2006 - m3		
Income level	Whole year	August	% difference
1	13.2	13.7	4%
2	12.3	12.7	3%
3	16.4	17.1	4%
4	28.3	28.4	0%
7	61.6	45.8	-25%
8	20.4	23.4	15%

Table 2-8 - Water use per connection for RR in 2006

	Monthly average 2006 - m^3		
Income level	**Whole year**	**August**	**% difference**
1	17.1	16.9	-1%
2	19.5	19.4	-1%
3	35.4	35.5	0%
4	58.7	60.6	3%

2.4.2. Coping mechanisms during periods of water scarcity

Water service disruption in the dry season, particularly in rural Filandia has meant that farms have had to look for alternative water sources.

Many larger farms have their own storage tank with a capacity for a few days of water use. Table 2-9 summarizes information about the size of the production system for each of the six farms in the key informant survey and the storage capacity of water in each of the farms. On farm storage capacity ranged from 0 to 18,000 liters and farms reported the ability to draw from reserves for one to five days.

Table 2-9 - Summary of survey results

User	Cattle	Pigs	Coffee	Water reserve capacity (liters)	Reserve duration (days)
Large farm	106	45		18,000	1
Large farm	100	115		5,000	3
Small farm	2	6		3,000	5
Small farm	18			1,000	1
Small farm	4		8 ha	4,000	8, or 2 (if sharing)
Small farm		33		0	1

The two primary schools surveyed have 9 and 17 students and for both of them there is a live-in care-taker family. They have reservoirs with a capacity for 1,000 and 5,000 liters respectively and can manage without the water service for 2 and 20 days respectively.

When the water shortages are prolonged for a longer period of time than the duration of the reserves, each farm and school have their own coping mechanism. One of the large farms installs a diesel water pump at a small stream (Buenavista creek) which requires having one person at the pump site while the water is being extracted. The other large farm brings water from the urban area of Filandia by truck during the day and reduces the washing of pig houses to every other day. Farms with stables stop using water for washing stables and collect manure with shovels. Small farms fetch water from creeks nearby by horse or by foot. They also bring water from the urban area of Filandia or from the municipalities below, depending on distance. Four respondents remembered 2004 as a very dry year and reported that the service was interrupted for periods between 10 and 12 days. The smaller school copes by operating for three hours until 10 am, and both schools collect water manually from small creeks in their vicinity.

The construction of individual tanks on-farm is related to farm size and income level (large production) implying that lower income households are impacted greater during shortages.

The farms located in the lower parts of the distribution area, in times of scarcity, are the last ones receiving the service. The water users in the upper part of the catchment fill their reservoirs and the small amount of water left in the distribution systems sometimes does not have enough pressure to reach the lower parts.

2.4.3. Water quality and effects on water availability

Water scarcity for domestic purposes can also be a consequence of torrential rain that produces soil erosion and suspended sediments in the streams, sometimes to a level that makes the water impossible to treat for potable use by water providers. Figure 2-1 shows that catchment Barro Blanco - BB, has the lowest level of total suspended sediments and Bolillos 2 – B2 shows the highest sediment loads throughout the year and particularly in both rainy seasons (Brown, S., 2008, personal communication). High sediments in catchment B2 is associated with high surface runoff from grasslands, direct access of cattle to the stream and drainage of a large wetland which lead to a large gully.

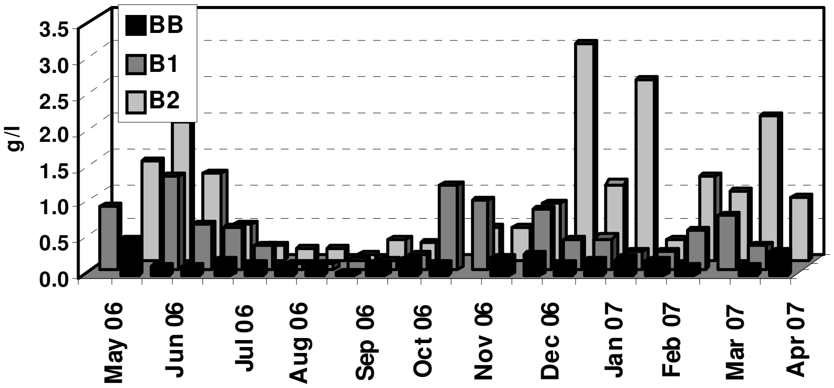

Figure 2-1 - Average total suspended sediments every two weeks in the three streams (Brown, 2008, personal communication)

Water scarcity is not a concern during the rainy season (March to May and October to December) to the same extent than during the dry season (June to September and January to February), but special treatment is required during the periods of heavy rain. The interruption of services due to sediments usually does not last for more than one day (Echeverry, 2009, personal communication). The municipality and water purveyors have done some conservation efforts on the farms that have allowed it, including fencing of riparian areas and wetlands in an attempt to reduce bank erosion.

2.4.4. Water scarcity index

The water scarcity index (IDEAM, 2000) is another mechanism to evaluate water availability versus use and provides an indication of pressure on local water resources. Results of the water scarcity index per month for the municipality of Filandia (rural and urban) are shown in Table 2-10. The detailed calculation method is included in Appendix 2.

The pressure on water resources according to this index can be classified in the following groups:

High pressure: water scarcity index over 40%
Medium pressure: water scarcity index between 20% and 40%
Moderate pressure: water scarcity index between 10% and 20%
Low pressure: water scarcity index below 10%.

Table 2-10 - Water scarcity index per month for 2006. Dry period: June to September

	with losses	**without losses**
Jan-06	7%	6%
Feb-06	9%	7%
Mar-06	5%	4%
Apr-06	5%	4%
May-06	7%	6%
Jun-06	9%	7%
Jul-06	32%	25%
Aug-06	77%	60%
Sep-06	71%	55%
Oct-06	8%	6%
Nov-06	3%	2%
Dec-06	5%	4%

As Table 2-10 shows, even the non-conservative calculation of the water scarcity index (not including losses) indicates that during two months of the year (August and September) the demand of water compared with availability is very high and the source is under high pressure. In July the water scarcity index is moderate and during the other months of the year, the pressure is low.

2.4.5. Water concessions for Filandia

Comparing the concessions granted to stream discharge provides an indication of water scarcity and whether the concessions granted are appropriate for the stream flows.

The concessions granted are 32 l/s for ESAQUIN and 7 l/s for RR corresponding to 101,088 cubic meters per month. Comparing this amount of water with the water that flows out of the two catchments (Table 2-11) the concessions are above the flows observed during the dry season. The concessions exceeded flow by 15,000 and 3,000 m^3 in Aug and Sep 2006 respectively.

Table 2-11 - Water flow per month from the three monitored catchments in cubic meters

water availability - m3/month	
Jan-06	978,033
Feb-06	691,748
Mar-06	1,164,175
Apr-06	1,486,905
May-06	941,858
Jun-06	767,715
Jul-06	211,835
Aug-06	85,797
Sep-06	97,895
Oct-06	800,771
Nov-06	2,034,776
Dec-06	1,260,184

Figure 2-2 compares the monthly water flows measured in the two streams Bolillos and Barro Blanco and the monthly water use charged to consumers by the two water providers in 2006. This illustrates the high fluctuation in water availability in the streams and the relatively small fluctuations in water use.

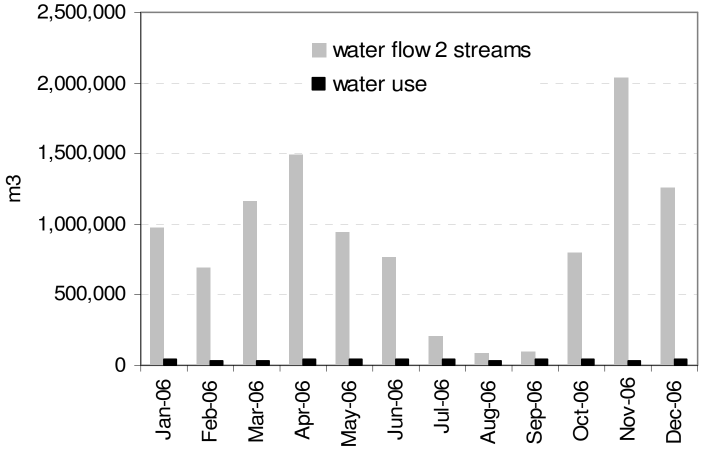

Figure 2-2 - Monthly water flow in Bolillos and Barro Blanco and water use in 2006

As shown in Figure 2-3, precipitation in the dry season (June, July and August) can vary significantly. 2006 was a year with an unusually wet June and an extremely dry September. July and August were under the average for the last 35 years. As shown In Table 2-12, 2004 was a drier year than the 35 year average.

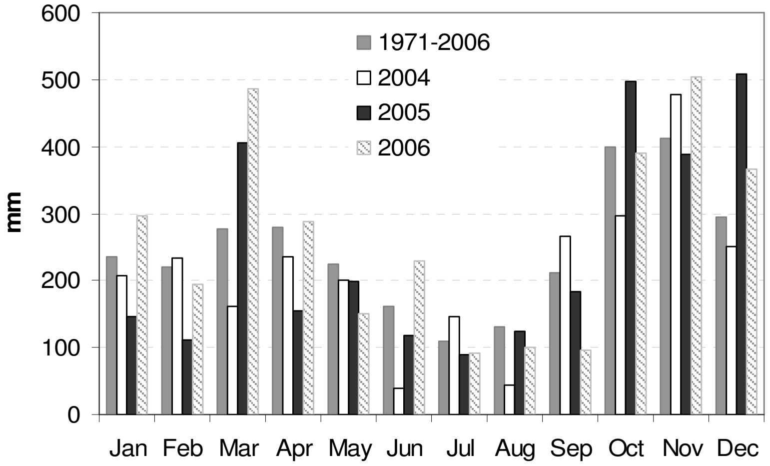

Figure 2-3 - Precipitation in the region since 1971.

The analysis of concessions versus water availability illustrates that streams are over allocated and that the high variability of precipitation and stream flow, and the lack or storage capacity were not considered when the concessions were granted. As the water demand grows, water shortages and disruptions in service are relatively common in the dry season. Options to reduce water use are limited since water use is already low. This suggests that the institutional / regulatory framework and water management are not consistent with the local reality.

Table 2-12 - Comparison of total precipitation for recent three years and a 35-year average

Annual precipitation	mm
1971-2006	2,955
2004	2,560
2005	2,927
2006	3,197

It is estimated that during 14% of the year 2006, the water concessions were above the water flow in the streams, considering the water available in the streams and the average water losses for the two water providers. Assuming no restriction on withdrawals of water from the streams, the flow characteristics and water use for 2006, water demand could be met by reservoirs with a capacity of 4,500 cubic meters and would prevent water scarcity during the dry period of August and September. This storage capacity is calculated assuming a daily water use of 1,680 m^3 per day which corresponds to the average water intake to the two distribution systems in 2006. It is assumed that ESAQUIN has losses of 25% and RR has losses of 40%; and that the water providers take all the water available in the streams when the flows are less than the concessions they have. However, if the streamflows are reduced by 5% and demand increased by 2% (which corresponds to the projected annual increase in demand by ESAQUIN for the next 25 years), only a reservoir of more than 6,700 m^3 could prevent water scarcity. According to estimates done by a water distributor in the region, a water reservoir with a capacity of 1,800 m^3 would cost around US$165,000 (Gómez, O., 2009, personal communication). ESAQUIN currently has a reservoir with a capacity of 1,000 m^3 and RR has a storage capacity of 500 m^3. Storage is a potential option to manage water shortages, however the challenge remains to find the financial sources to build additional infrastructure.

The access that water providers are having to consolidated resources through the Regional Water Plan, and the requirements of providing short, medium and long term vision of investment needs are allowing water providers to include water storage in investment plans. In the case of ESAQUIN, the enterprise has so far geared its limited investments towards replacing old pipes and expanding service coverage but is preparing an application to the Water Plan. Water Plans are seen by water providers as an opportunity to consolidate the services in urban areas. The Regional Water Plan for Quindío, where Filandia is located has funds for approximately US$32 million for 11 municipalities (Echeverry, 2009, personal communication).

2.5. Summary

The evolution of the institutional framework for water provision in Colombia has created an urban bias. The tariff structure, designed to distribute financial resources between socio-economic groups is only appropriate for large urban areas where the number of users paying over charged tariffs is enough to generate enough income to cover the subsidies for users in lower income groups. Small water providers in rural areas or small municipalities where most of the population is concentrated in lower income groups are consequently under funded for the improvement and maintenance of water storage infrastructure. The main consequence of this is that water users are left on their own for the provision of storage facilities as was evidenced by the results of the survey.

The case of water provision in Filandia illustrates the consequences of the current water institutional framework at two scales: municipal and individual household / farms. At the municipal scale, water providers for small municipalities do not have the resources to build infrastructure to adapt water supply to the natural fluctuations in water availability. The water provider for the urban area, ESAQUIN is a larger company that supplies water to seven municipalities, but the majority of its clients are water users of the lower income groups. The enterprise is under funded and is preparing an application to the Regional Water Plan to increase coverage to a semi-urban area of Filandia and other similar communities in the region, and build reservoirs for the provision of water during the dry season. The RR is a community water provider, whose water intake is below the water intake for ESAQUIN and has a reservoir for 500 m^3. Therefore, during times of scarcity, its rural clients are the first ones to be impacted by water shortages. The uneven temporal distribution of water availability is translated to the water users that have to build and maintain their own storage.

Although water providers have an incentive to allocate scarce water to higher income level groups that pay higher tariffs for their water, this situation cannot be diagnosed with the available data.

However, it is worth noting that income level 4 is the only household group that had an increase in water use during the dry season of 2004. The unequal distribution of water scarcity occurs at an altitude gradient. The farms located in the lower parts of the distribution area, in times of scarcity, are the last ones receiving the service. The water users in the upper part of the catchment fill their reservoirs and the small amount of water left in the distribution systems sometimes does not have enough pressure to reach the lower parts.

The integration of knowledge of the biophysical response of ecosystems to precipitation, into water policies and water management, is required to ensure an adequate water supply under local conditions. There is a need to understand the mechanisms that determine the biophysical reduction of water supply, and the processes governing the water regulation capacity of the headwater catchments.

The legal framework aims at providing equal access to all the population, and through the regulation of prices, it has achieved significant reductions in water use; however, on the supply side, concessions are granted regionally regardless of availability and fluctuations; and the construction and development of infrastructure for storage and distribution is done by water providers that only in large municipalities, have the resources to ensure continuous supply of water. Through the newly designed Regional Water Plans, the national government has designed a mechanism to improve the infrastructure for water service provision at the regional scale. These resources provide the opportunity for water enterprises to design and build water systems that account for local variations in water availability.

It is within the institutional framework that water provision for all can be achieved. Small rural communities rely on natural flows for a constant supply of water. Many small communities are located near headwater regions of catchments. Thus the biophysical settings (geology, soils, topography and climate) are important factors to achieve equitable water supply. While small communities cannot afford the construction of infrastructure for water management, the institutional framework should integrate the ecological / biophysical realities of headwater catchments, so that these communities limit their vulnerability to water shortages.

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3. Water flow characteristics of small wetlands in headwater catchments of the tropical Andes[1]

3.1. Introduction

The debate about the role that headwater wetlands play as water quantity regulators both in the maintenance of dry season flows and in holding water during storm events has not been resolved. Scientific contributions since the 1960s have presented conflicting evidence of the role of wetlands for both functions. In 2003 Bullock and Acreman summarized the studies about possible wetland functions, reporting that 47 of 71 studies concluded that wetlands reduce the flow of water in downstream rivers during dry periods. Evidence was mainly from North America and Europe but there were a few case studies from Sierra Leone and Southern Africa. The main supporting evidence for this observation is that 22 out of 23 studies show that evaporation from wetlands is higher than from non-wetland portions of the catchments during dry periods. However, according to their summary, in 20% of the cases, wetlands increase dry season flow (Bullock and Acreman, 2003). Since 2003, studies have continued to be divergent. In 2004 a review of the hydrology of dambos (tropical and subtropical African wetlands) by von der Heyden (2004), concluded that bearing in mind the high variability in dambo characteristics, base flow and dry season flow augmentation is a function primarily of groundwater recharge, with a secondary contribution from surface water storage within the dambo.

In terms of storm flow attenuation, Bullock and Acreman (2003) found that for wetlands in headwaters of river systems, 30 of 66 studies show that wetlands reduce or delay floods and a substantial number of studies (27 of 66) show that headwater wetlands increase flood peaks. These studies were conducted mostly in Europe but included cases from West Africa and Southern Africa. For dambos, von der Heyden (2004) found that storm flow is retarded or attenuated during the early wet season through soil infiltration and dambo filling with the extent of the retardation being a function of the soil type and antecedent moisture characteristics.

More recently there has been an interest in the concept of hydrological connectivity which is defined as the efficiency with which runoff moves from source areas to streams and then through the stream network (Herron and Wilson, 2001). This concept can help explain the contributions of wetlands to the streams below them, by providing a framework for the analysis of factors that influence their hydrology. Bracken and Croke (2007) proposed a conceptual framework for hydrological connectivity which includes hillslope runoff potential, which in turn is influenced surface roughness, vegetation and land management among other factors.

There are limited publications about the extent of wetlands in mid elevation headwater catchments (between 1,000 and 3,000 m.a.s.l.) particularly in tropical mountain regions and they have not

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[1] A version of this chapter will be submitted for publication
Roa-García, C., Lavkulich, L., Brown, S., Water flow characteristics of small wetlands in headwater catchments of the Colombian Andes.

been sufficiently described in terms of their hydrological behavior and edaphic characteristics. Headwater wetlands in the tropical Andes continue to be impacted by human activities. In Colombia, cattle grazing and drainage for the expansion of agriculture are the main activities impacting wetlands in these headwater regions. Recent analyses have affirmed that the degradation and loss of wetlands globally is more rapid than those of any other ecosystem (Millennium Ecosystem Assessment, 2005; Davidson and Finlayson, 2007). Headwater wetlands rank among the world's ecosystems most threatened by human actions. They can be destroyed in a matter of days, but require hundreds of years to form naturally (Krecek and Haigh, 2006).

This paper aims at providing a characterization of the wetlands located in three small tropical headwater catchments on the western slope of the central branch of the Colombian Andes (altitude between 2,000 and 2,200 m.a.s.l.). The study provides a hydrological analysis of three wetlands chosen to compare their hydrological behavior (one in each of the three catchments), and examines the role these wetlands play in catchment hydrology in the tropical Andes.

The catchments have a total area of 400 ha and the water coming out of these headwaters is the source for the entire municipality of Filandia, a town of approximately 15,000 people, and for their economic activities, which include mainly cattle production, coffee and other agricultural products, as well as recreation (hotels).

Water providers and municipal and provincial environmental authorities believe that small wetlands located in these headwater catchments regulate water flows by contributing to base flow during dry seasons and dampening extreme flow events. A previous semi-quantitative assessment of the hydrology of these wetlands showed an overestimation of their size and an annual surplus water balance (CRQ, 2001). This led the municipality to embark on a conservation program in agreement with some of the land-owners with the goal of improving water supply.

The goal of this study is to contribute to the understanding of headwater wetlands by quantifying their surface outflows and assessing the role they play in the maintenance of dry season flows and the attenuation of storm events. The analysis will evaluate: 1) the contribution of headwater wetlands to base flows during the dry season relative to the size, topography and degree of disturbance of the wetland and its contributing area; and 2) the role of wetland size in water storage capacity and storm water flow regulation. From these results, general recommendations will be made about management options for headwater wetlands and their contributing areas.

Wetland soils are rich in organic matter and in many cases they act as carbon sinks because the decay processes are slower than the production of organic matter. Since the content of organic matter in soils is one of the most influential factors for water holding capacity of soils, the rates of organic matter accumulation will be estimated.

3.2. Study site

The catchments and wetlands selected for this study are located in the coffee growing region of Colombia (4.67º N, 75.63 º W) at 2,000 – 2,200 m of elevation. Most of the land use in the three catchments is dominated by extensive cattle grazing for milk production, beef, and bulls sold for bullfighting. The decline in coffee prices since the mid 1990s and the increase in cattle and meat prices in the last few years have stimulated the expansion and intensification of cattle ranching in the three catchments with a corresponding impact on non-protected wetlands. Some of the wetlands have been fenced by the water enterprises and municipality to prevent cattle from entering the wetland areas, as the wetlands are believed to contribute to water flow particularly during the dry season.

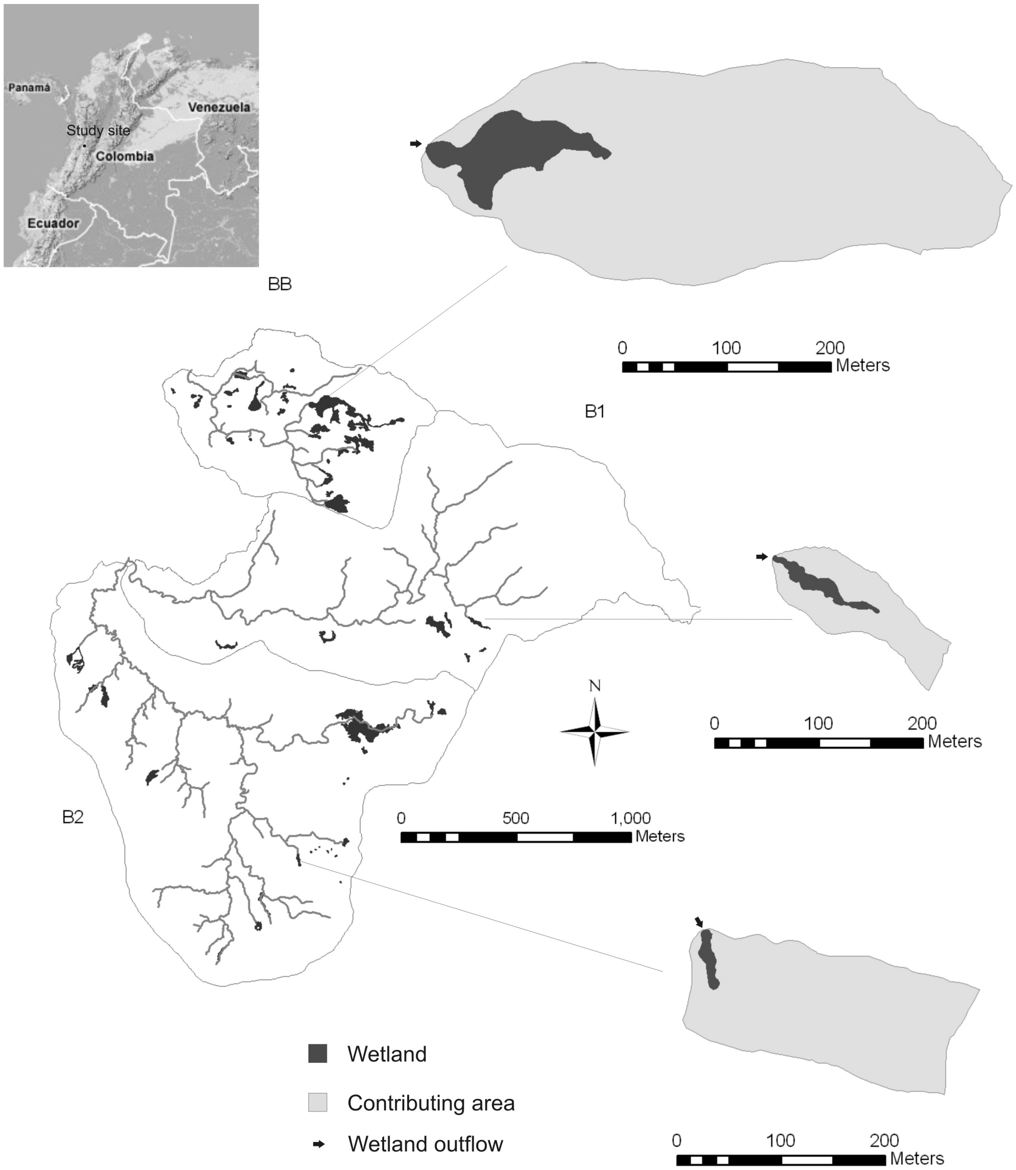


Figure 3-1 - Location of the three monitored wetlands in the three catchments. All wetlands have surface outflows connected to the stream network.

The catchments (Figure 3-1) under study are called Barro Blanco (White Mud in Spanish referring to the volcanic ash layer seen in parts of the catchment) and Bolillos (the name of an endemic palm tree that grows in the area). For this study the Bolillos catchment was divided in two smaller units Bolillos 1 and Bolillos 2, corresponding to the main tributaries. For convenience the catchments and the corresponding wetlands selected for the detailed monitoring are referred to as BB, B1 and B2 respectively.

3.2.1. Geology and soils

The three catchments of the study are located in the Quindío-Risaralda Fan composed of a mass flow of fluvio-volcanic sediments deposited during the last million years above a Cretaceous volcanic and metamorphic basement. The Fan is composed of 12 distinct units that vary according to their composition, direction and chronology. The unit where the study site is located corresponds to one of the oldest units of the Fan, exhibiting a dominantly east-west trending flow direction with a hummocky topography (Guarín, et al., 2006) which has been conducive to the formation of wetlands. The sediments are mostly clays of uniform size and arranged with pockets of crystalline coarse fragments. The unit has a volcanic ash layer of variable thickness, which can reduce the rate of water percolation.

Soils formed on these sediments are classified as Andisols (Acrudoxic Hapludans) (IGAC, 1996). The principal soil-forming process has been the rapid weathering (transformation) of volcanic ash to produce amorphous or poorly crystallized silicate minerals. In general Andisols are not pedogenetically mature, however, the term ‘oxic’ is used to describe highly weathered, primarily mixture of iron, aluminum oxides and non-sticky-type silicate clays (Brady & Weil, 2002). After Histosols, Andisols are the soils with the highest organic matter content which, in combination with their high content of allophanes and imogolite, result in light soils of low bulk density, with high water holding capacity and resistant to erosion by water.

3.2.2. Climatic conditions of the region

Central Colombia and the western Andean cordillera experience a bi-modal annual precipitation cycle where rainfall peaks during April–May and October–November, and is low during December–February and June–August, mainly as a result of the double passage of the Inter-Tropical Convergence Zones (ITCZ). The seasonal strengthening of the Chocó Jet (September–November) and weakening (February–March), partially explains why the October–November rainy season is more intense than that of April–May over central and western Colombia (Poveda et al., 2006).

3.3. Methods

The wetland characterization describes the physical properties of the wetlands that could explain their hydrological behavior. It includes bathymetry of the wetlands, vegetation diversity, water temperature, size of contributing area, estimation of decomposition rates of organic materials as well as soil bulk density and organic matter content.

The objective of the hydrology monitoring program was to generate time series of the water inputs and outputs for each of the three selected wetlands. The variables measured were wetland water storage (level and volume), wetland discharge (wetland outflow), stream discharge, precipitation in each of the wetlands micro-catchments and the necessary variables to calculate potential evapotranspiration – PET.

The data was collected using automatic equipment that allowed the collection of data at 15 min intervals which was considered an appropriate time resolution to analyze hydrological response.

3.3.1. Wetland characteristics

3.3.1.1. Wetland inventory

The quantification of wetland area for the three catchments required the adoption of a definition for wetlands applicable to headwater wetlands. Because wetland characteristics are so variable with respect to location, climate, size and gradation from aquatic to terrestrial, definitions of wetlands are to some extent arbitrary, and as a result there is no one single universally recognized definition of a wetland (Mitsch & Gosselink, 2000). For the purpose of this study, a wetland is an ecosystem that arises when inundation by water produces soils dominated by anaerobic processes and forces the biota, particularly rooted plants, to exhibit adaptations to tolerate flooding (Keddy, 2000). Wetlands exist in places that as a result of geomorphological characteristics and water regime allow the accumulation of standing water that, in combination with soils, create unique conditions in the landscape. Using this definition, the wetland inventory done for the study site includes areas where plant communities depict distinctive characteristics even if the soils are not saturated during the entire year.

The inventory was conducted as part of a land use map for the three micro-catchments where the wetlands are located. The map was developed using a 2003 satellite QUICK BIRD image with a resolution of 0.6 meters taken in 2003 combined with the use of a GPS and field surveillance. The field mapping was subsequently transferred to ArcGIS© for spatial analysis. The wetlands were classified according to: whether they are temporary / permanent, fenced / not fenced, whether they have a surface outflow and whether they have a water source different from rain. Using this classification, three wetlands were chosen for the monitoring program (Figure 3-1). The chosen wetlands were easy to access, had rain as the only water source and had a surface outflow. Two of them had a fence at their boundary (the limit between the permanently saturated soil and the non permanently saturated soil) and the third one was not fenced. The three wetlands are located in the lower part of the contributing area and their surface outflow corresponds to the point of discharge of the contributing area.

3.3.1.2. Wetland plant inventory

From each of the three catchments studied, three wetlands were selected for a total of nine to complete a plant inventory. This was done using 2 m by 1 m quadrants on north to south and east to west transects located every five meters. Each plant found in each quadrant was classified and its area of coverage was estimated on a percentage basis for each quadrant and then extrapolated to the overall wetland. This was also done in the area of transition between saturated and non saturated soil and 10 meters away from the wetlands to analyze the dynamics of plants between the wetlands and surrounding areas.

3.3.1.3. Wetland water temperature and pH

Water temperature was recorded using HOBO$^{©}$ Water Temp Pro loggers with an accuracy of 0.2 °C at 25°C. These devices were submersed at a 20 cm depth in the wetlands for a year from June 2005 until May 2006. pH was recorded once during a wet season (in April 18th, 2005) and once during a dry season (in June 16th, 2006) using a HOBO$^{©}$ pH meter.

3.3.1.4. Wetland organic matter and decomposition

Several analyses can be performed to understand processes of carbon accumulation and the role of ecosystems as carbon sinks or sources. For this study, two principal methods were used: carbon content measurements of soil samples using loss on ignition and estimation of rapid decomposition rates using the litter bag technique. Carbon content was measured using the loss on ignition method – LOI (Nelson and Sommers, 1996), and cross checked for selected samples using the Walkley Black chemical oxidation method and LECO (dry combustion) carbon analysis (Schumacher 2001). The numbers of samples analyzed were 48 for wetland BB, 21 for wetland B1 and 16 for wetland B2.

Potential plant decomposition rates were evaluated through the litter bag technique (Swift and Anderson 1989). Samples of three dominant wetland and pasture grasses were collected in the field and oven dried at 40 °C for 48 hours. 10 x 10 cm nylon mesh bags with a 1 mm opening were filled with about 10 grams of dried leaf litter. A total of 12 bags were filled for each plant species. Each sample was weighed separately, the initial weight was recorded and the sample labeled numerically. The 1 mm mesh size is sufficiently small to prevent the loss of litter but permits the access of decomposers.

The experimental layout was 12 spatial replicates for below ground decomposition at 2 sites: wetland (saturated) and pasture (unsaturated). The bags were labeled with a plastic plant tag tied to the bag with nylon line and buried at 20 cm depth. Two bags of each plant (Juncacea, Poacea and Cyperacea) were sampled every 4 months at each of the 2 sites (wetland and pasture). The samples were carefully washed to remove excess soil, oven dried (40 ^{o}C for 48 hours) and weighed to record final weight. The final weight represents the mass remaining after decay; the percent of initial mass remaining was then calculated. Decomposition was determined by the rate of mass loss plotted over time (2 years).

3.3.2. Wetland hydrology

3.3.2.1. Climate monitoring

Three data logging rain gauges were installed in the three catchments, to accurately measure precipitation of the headwaters where the wetlands are located. These rain gauges were installed in August 2004 at elevations between 2,100 and 2,135 meters.

The variables used to estimate potential evapotranspiration (PET) are given in Table 3-1. PET represents a hypothetical upper limit to actual evapotranspiration (Moore, 1999). PET was calculated using the Penamn combination equation taken from Dunne and Leopold (1978), with daily data and summed for each required time period (e.g. weeks or months) using Interactive Data Language - IDL©.

Table 3-1 - Climate variables and instrumentation

Variable	Instrument
Precipitation	4 Hobo Pro© data logging rain gauges
Air temperature	HOBO Pro© sensor with data logger
Relative humidity	HOBO© relative humidity sensor with data logger
Wind speed	Totalizing anemometer
Solar radiation	Onset Silicon Pynanometer Smart Sensor©

Because the supply of water is seldom considered limiting in many types of wetlands (Mitsch and Gosselink 2000), the theoretical atmospheric demand or potential evapotranspiration (PET) is used to approximate wetland evapotranspiration rates (Lott and Hunt, 2001). Evapotranspiration is assumed equal for the wetland and the contributing areas. Since relatively small differences have been found in calculating PET with different meteorological methods (Lott, 1997), only the Penman combination method was used. The full description of this method is summarized in Appendix 2.

To analyze the response of wetlands to different types of rain events, these were defined and classified. Rain events were defined as the precipitation equal or larger than 2 mm that ends when there has been no precipitation for the following 2 hours. A classification of events into five types was done based on the duration, the total precipitation and the 30 minute intensity of each event: type 1, small events (less than 10 mm in total amount of rain); type 2, medium size events of low intensity (10-20 mm of total precipitation and less than 10 mm of max I30); type 3, medium size events of high intensity (10-20 mm of total precipitation and more than 10 mm of max I30); type 4, large size events of short duration (more than 20 mm of total precipitation during 5 hours or less); and type 5, large size events of long duration (more than 20 mm of total precipitation during more than 5 hours). The classification of events is described in Appendix 3.

3.3.2.2. Wetland and stream monitoring

To determine the hydrological characteristics of wetlands and their contribution to the catchment discharge, one wetland in each catchment was selected for monitoring based on accessibility and degrees of conservation. The three contributing areas of the wetlands are used for cattle grazing with varying intensity. B2 had a fence around the wetland in good condition, B1 is not fenced and BB has a fence in poor condition.

Each wetland has a particular bathymetry that determines its water storage capacity. For each wetland, depth measurements were taken with an extended Russian peat corer following transects at known distances. The depths of the organic matter layer of the wetland soil were entered into ArcGIS© to generate ASCII files used in the calculation of wetland water volumes with IDL© and to generate the wetland 3D profiles using Surfer©. The water storage capacity of each wetland soil was measured using a number of soil samples that were analyzed for water content. This was then multiplied by the wetland volume calculated with Surfer©.

The surface water outflow of the three chosen wetlands was monitored through continuous measurements of water level using Odyssey® capacitive water level recorders (Dataflow Systems, New Zealand, 2002). Water level was recorded every 15 minutes from June 2005 until May 2007 at the three wetland outflows. Flow measurements were taken using the salt dilution method (Moore, 2004). This method is considered accurate for small streams with irregular channels (Dingman, 2002). Stage-discharge relationships were developed using 15, 22 and 14 discharge measurements for wetlands B1, B2 and BB respectively.

Streamflow at the catchment scale was monitored at the outlet of the three catchments with three AquiStar PT2X Smart Sensors®. Water level was recorded every 15 minutes from June 2005 until May 2007. These water level data series were converted into flow measurements with stage-discharge relations by 62, 44 and 50 discharge measurements for catchments B1, B2 and BB respectively using a current meter from OTT© – Messtechnik GmbH & Co. The data series collected for wetland surface outflows and streams were analyzed using IDL©, to conduct specific analysis.

3.4. Results and discussion

3.4.1. Wetland characteristics

3.4.1.1. Wetland inventory

The results of the wetland inventory show that catchment BB has the largest wetland area, with 3.8 hectares or 6.1% of the catchment area. For catchments B1 and B2 the areas of wetlands are 0.8 and 2.6 hectares corresponding to 0.5% and 1.5% of the catchment area, respectively. The results of this inventory are summarized in Table 3-2.

Table 3-2 - Wetland inventory

Catchment	Number of wetlands	Area of wetlands (ha)	Total catchment area (ha)	% area of wetlands
BB	23	3.8	62	6.1%
B1	7	0.8	158	0.5%
B2	22	2.6	170	1.5%
Total	52	7.2	400	2.0%

A total wetland area of 7.2 ha is significantly lower than the overestimated 38.2 ha of wetlands reported by CRQ in 2001. The largest wetland is located in catchment B2 and has an area of 1.5 ha. The complete inventory is included in Appendix 4. Of the 52 wetlands in the inventory, only three wetlands are larger than 0.6 ha.

3.4.1.2. Wetland soils and water volume

A reference volume for the wetlands was selected to facilitate the comparison of the water storage capacity of the three chosen wetlands. The porosity, volumes of water stored in each of the three wetlands on August 16 2006 at 12:00 pm, the wetland areas and the catchment areas are shown in Table 3-3. The reference volume was chosen on a date in the dry season where the water level in the wetlands is already receded but has not reached its minimum.

Table 3-3 - Wetland area, contributing area, wetland volumes and percent porosity

Wetland	N	Porosity of wetland soils (%)	Wetland area (m^2)	Contributing area (m^2)	Wetland area: Contributing area ratio	Contributing area slope	Water volume (m^3)
B1	8	79	1,070	9,850	1:9	0.8	440
B2	8	91	550	25,600	1:46	0.9	610
BB	10	86	6,650	89,050	1:13	0.2	3,720

There are significant differences in the bathymetry of the three wetlands and topography of their contributing areas. B2 is a deep wetland (maximum depth of 2.75 m) with a contributing area that is steep and large in relation to the wetland area. B2 also has the highest soil porosity. B1 has the smallest contributing area which is steep on all sides of the wetland which has a maximum depth of 2.1 m. BB is the largest wetland and has a significant contributing area with a more level/gentle slope, and the wetland has a maximum depth of 2.4 m. One of the major effects of the differences in the bathymetry and topography of the wetlands and their contributing areas can be seen in the temporal variation in the water levels of the wetlands (Figure 3-2).

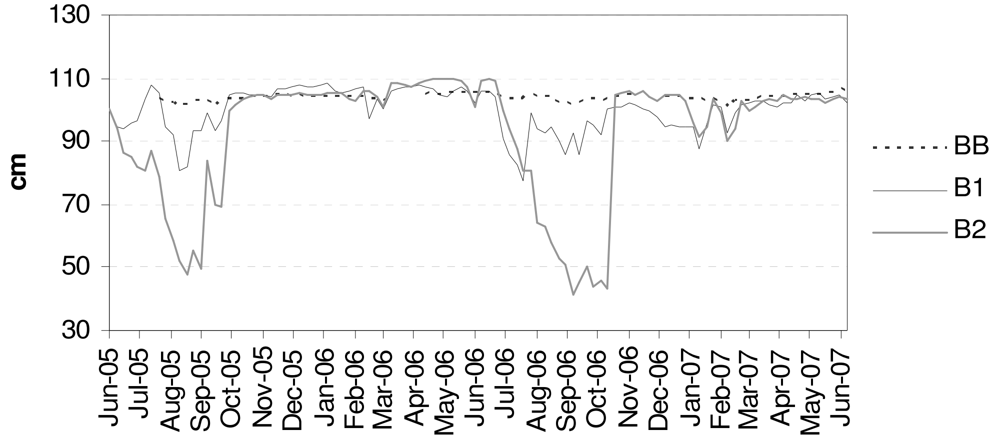


Figure 3-2 - Temporal variation in wetland water level from June 2005 until June 2007

3.4.1.3. Wetland plant inventory

The dominant plant of the entire plant inventory in the nine wetlands was *Eleocharis maculosa (Vahl) Roem. & Schult.*, considered a wetland plant, with a 20% coverage of the total wetland area of 4.2 ha. Out of the 87 plants species found inside the wetlands, only seven are found exclusively inside the wetlands and they occupy 2.6% of the total area; six plants are found both inside the wetland and on the wetland boundary, covering 2.5% of the wetland areas. The other 74 plants were found inside and outside the wetlands.

Differences in the vegetative cover of the three wetlands chosen for the hydrological analysis are shown in Table 3-4. Wetland B1 has the smallest number of plant species (23) and the five dominant plants cover the largest percentage of area (78%). B2 is relatively similar with 30 plant species and 75% of its area covered by five dominant plants, and it is the wetland with the largest area dominated by one single species (53% by *Juncus effusus L.*). BB, the largest wetland has 53 species. BB is the only wetland whose dominant plant is found exclusively in water saturated soils.

Table 3-4 - Summary of wetland plant inventory in the three chosen wetlands

Wetland	Number of quadrants	Number of plants found	% coverage 5 dominant plants
B1	15	23	78
B2	12	30	75
BB	37	53	51

A list of the five dominant plants in the three monitored wetlands is included in Appendix 5.

3.4.1.4. Wetland water temperature and pH

The comparison of water temperature for the three wetlands in relation to air temperature shows that both air and water temperature had the highest variability in the dry season (months of July, August and September).

The monthly median water temperature in wetlands BB and B2 show a small variation within each month and an annual trend that is opposite to the annual trend for air temperature: it is lower in the months where air temperature is higher (July, August, September) and is higher in the months when mean air temperature is lower (October, November, December) as shown in Figure 3-3. Water temperature for wetland B1, which is a shallower wetland, behaves in a similar way to air temperature, with a wider range of variation within each month and a similar pattern in the annual variation.

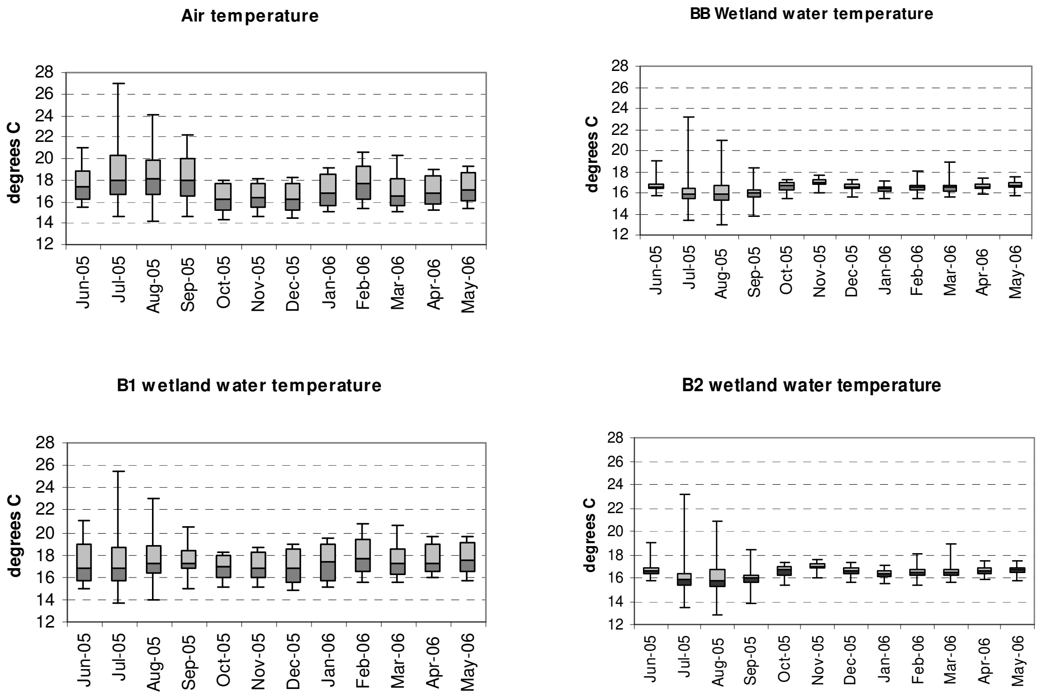


Figure 3-3 – Lower quartile, median, upper quartile, and min. and max. observations of monthly air temperature and wetland water temperature.

The water pH in the three wetlands is slightly acidic averaging 5.9 and there is no significant difference between them.

3.4.1.5. Wetland organic matter and decomposition

The organic matter content in relation to depth for the three studied wetlands is given in Figure 3-4.

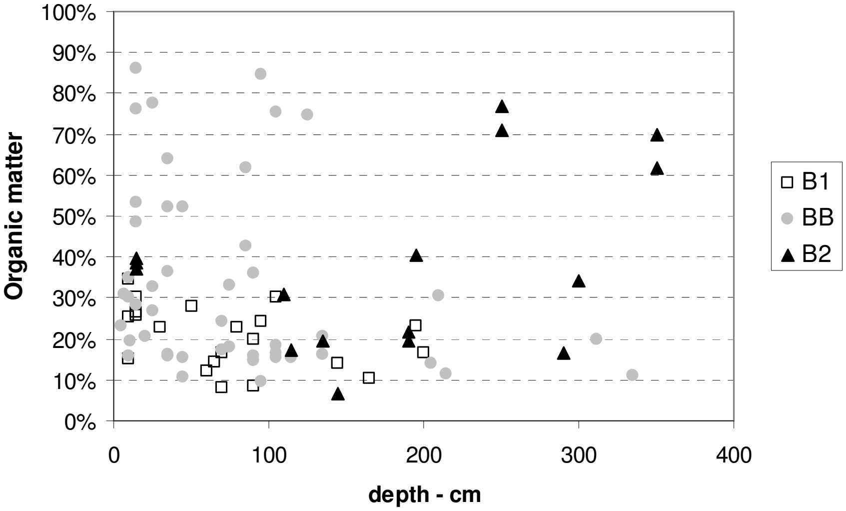


Figure 3-4 - Organic matter content of wetland soils in relation to depth

The average organic matter content at all depths for the three wetlands is 20% for B1, 38% for B2 and 33% for BB. B1 has a low amount of organic matter, being the most disturbed wetland; B2 shows a higher amount of organic matter at greater depths; and BB shows a higher amount of organic matter at shallow depths. In comparison, tropical wetlands of Micronesia have between 20% and 47% organic matter depending on the input of sediments which was related to the location of the wetland (Chimner et al., 2005), while organic matter content in mangrove peats in Belize range between 50% and 90% (Cameron & Palmer 1995; McKee & Faulkner 2000).

In a previous study, two soil cores were collected from the BB wetland and carbon dated (Muñoz, 2007). Her results revealed an age of 5,150 years at 2.9 meters of depth. Using these data, the rate of accumulation of organic matter was calculated to be approximately 7 cm per 100 years (and 17 cm every 100 years in the last 200 years). These average values are higher than the rate of accumulation for temperate and boreal wetlands which are typically < 10 cm / 100 years, and are often below 5 cm / 100 years (Gorham, 1991).

The characteristics of the decomposition process were studied through the litter bag experiment and the results are summarized in Figure 3-5. The waterlogged conditions of BB promote anaerobic conditions and a low rate of organic matter decomposition, contributing to the build-up of organic matter despite relatively warm temperatures throughout the year.

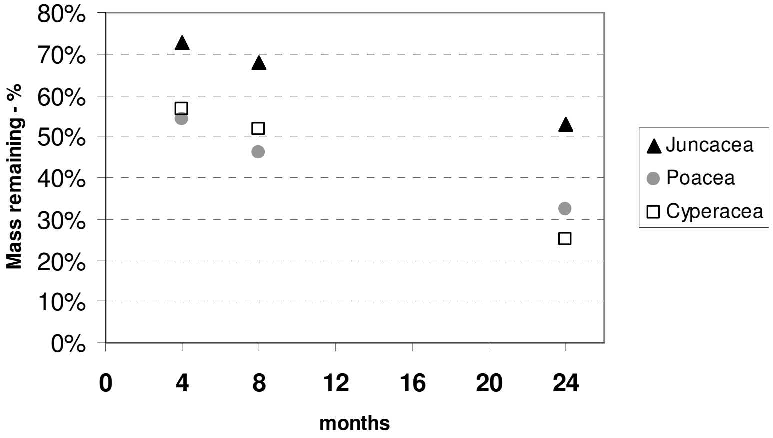


Figure 3-5 - Percentages of mass remaining in decomposition bags

The results of the measurements of the litter bags showed that after 24 months, the mass of organic matter remaining in the decomposition bags was between 25% and 52% of the initial mass, depending on the plant species (Fig. 3-5). The average air temperature was 16.5 º C. These values contrast with 12 -21% mass remaining in well drained soils. A similar study done in Micronesia by Chimner (2005) reported that after 17 months the remaining mass of organic matter was 20% in wetlands where the average air temperature was 27 º C. These results suggest that at a 10 º C cooler tropical environment decomposition processes are significantly slower. In comparison with litter decomposition in well drained soils of different latitudes, these decomposition rates are comparable to the ones observed at high latitudes (40 degrees North or higher) (Zhang, et al., 2008).

The wetland characteristics described in this section indicate that the three wetlands are significantly different in terms of ecosystem disturbance. B1 can be described as a highly impacted wetland, with lower soil porosity, lower organic matter content, significantly higher water temperature, and a reduced number of wetland plants in comparison to the other two studied wetlands. B2 can be described as a dynamic wetland, that shows large fluctuations in water level due to its steep surrounding topography, large contributing area and high porosity, and despite being the smallest wetland in terms of area, it hosts a larger number of plants than B1; this wetland also has the highest values of organic matter at lower depths. BB is the wetland that shows the smallest water level fluctuation, and the largest number of wetland plants, factors related to its larger area; it has the highest percentage of organic matter content at shallow depths, compatible with the more constant saturation conditions (less water level fluctuation). These differences contribute to the explanation of the hydrological response of each of the three wetlands.

3.4.2. Wetland hydrology

3.4.2.1. Dry season wetland outflows

The dry and wet seasons were determined for the June 2005 – May 2007 period using the precipitation data collected with four rain gauges. During these two years, the three wetlands ceased to produce surface outflow when the stored water level decreased as the dry season advanced. The percentage of days in the monitoring period during which the wetlands had no surface outflow is given in Table 3-5.

Table 3-5 - Percentage of days when wetlands have no surface water outflow (June 2005 – May 2007)

	% days with no surface outflow		
	Wet season	**Dry season**	**total**
B1	14%	48%	30%
B2	3%	52%	25%
BB	4%	33%	18%

Wetland outflows B1 and B2 are dry for half the time during the dry seasons and BB's is dry a third of the time during the dry season. The wetlands stop producing surface outflow when the cumulative precipitation in the previous four days is below 67 mm for B2, 60 mm for BB and 40 mm for B1 on average.

The flow duration curves presented in Figure 3-6a represent the percentage of time during which a selected discharge may be equaled or exceeded (Shaw, 1988) and it compares the 3 wetlands. This shows that when it rains, outflow from wetland BB is greater than for the other 2 wetlands which is a consequence of the size of its contributing area. What is interesting from this graph is that although B2 is the smallest wetland with a contributing area of intermediate size, its lowest flows are larger than for the other 2 wetlands. This is explained by the connectivity given by its open water surface. The curve for B1 shows that although its contributing area is smaller that B2's the high flows are higher, indicating a reduced water holding capacity.

The flow duration curves shown in Figure 3-6b were constructed using the mean daily discharge in a dimensionless form and the cumulative frequency expressed as a percentage of the total. In this case, the wetland outflow is compared with itself and what should be interpreted is the shape and gradient of a flow duration curve which gives a good indication of a catchment's runoff response to precipitation (Burt, 1995). A flat curve would indicate a reliable sustained flow. Therefore it is possible to say that B2 has a less flashy response to precipitation in comparison with the other 2 wetlands.

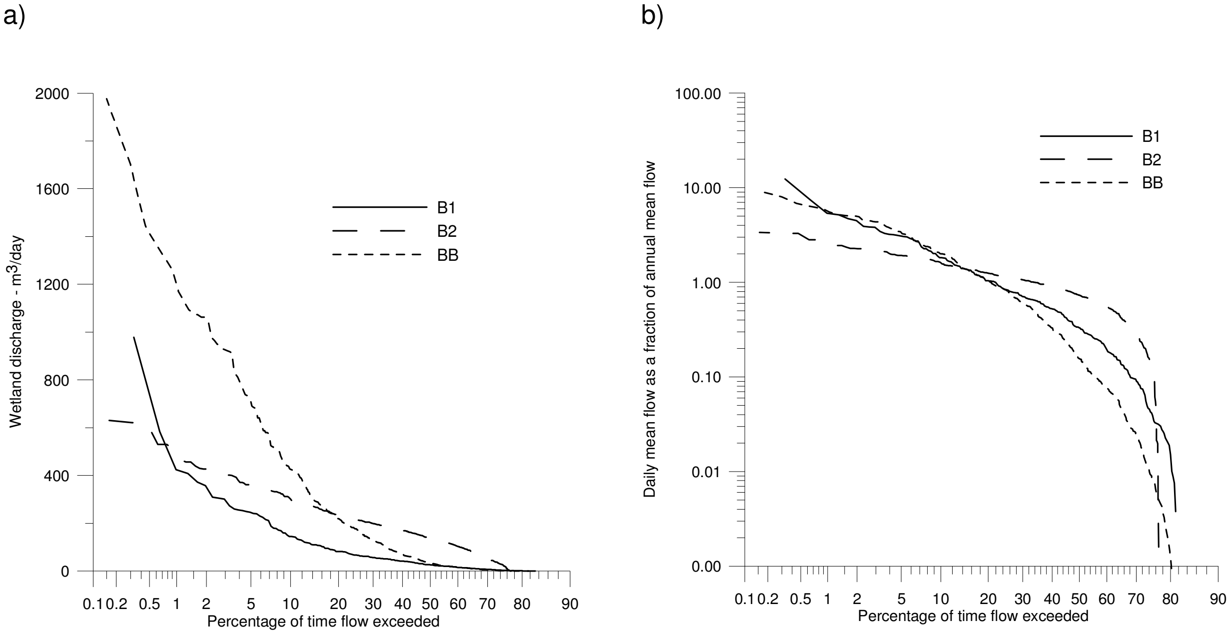
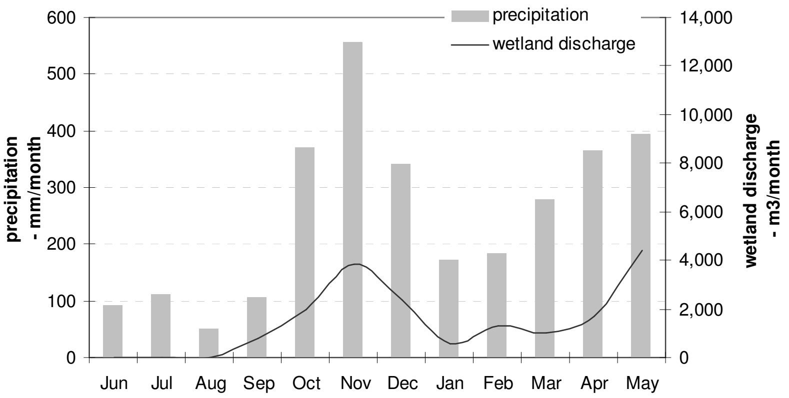


Figure 3-6 - Flow duration curves: a) wetland discharge; b) daily mean discharge as a fraction of total mean

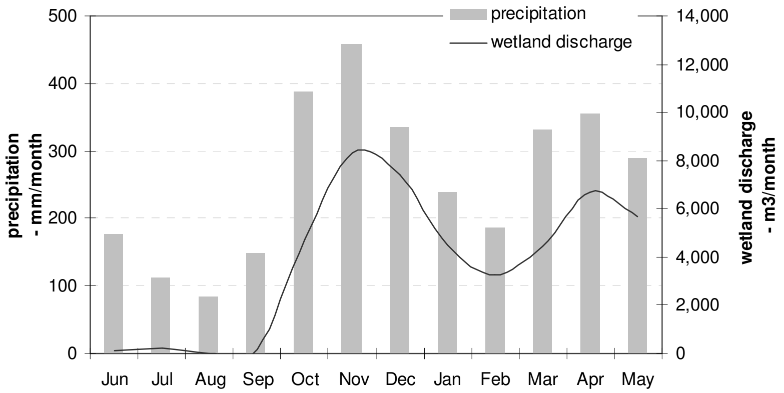
The total monthly wetland outflow shows the behavior of the wetlands particularly in the dry season. The outflow of B1 wetland remains dry during the dry season from June to August (Figure 3-7a) and as soon as the rains start in September it begins flowing again; B2 seems to respond with a lag to the decrease in rain (Figure 3-7b) and the flow in September is still low. This suggests that the wetland has emptied in the previous months. BB shows a clear lag in time during the dry season presenting a gradual decrease in flow, never reaching zero flow for an entire month (Figure 3-7c). In September / October BB seems to be recharging since the outflow does not reflect the amount of precipitation. None of the wetland outflows dry out in the short dry season from January to February.

These graphs illustrate the effects of the wetland physical properties on discharge. The size of the contributing areas is reflected in the magnitude of the monthly discharge of the three catchments, but BB's discharge is not proportional to the size of its contributing area, which can be explained by its flatter topography and its larger wetland volume. The flatter topography of BB could also explain the larger monthly discharge of this wetland in the last month of each rainy season (November and May) when the wetland "bursts" and releases water stored during the previous rainy period. B2 on the other hand, does not appear to store much of the water in the rainy season, but responds proportionally to precipitation on a monthly basis. Although BB wetland has a higher discharge (m^3/month) than the other two wetlands, these numbers are small and none of the three wetlands make a significant contribution to dry season flows.

a) B1 wetland



b) B2 wetland



c) BB wetland

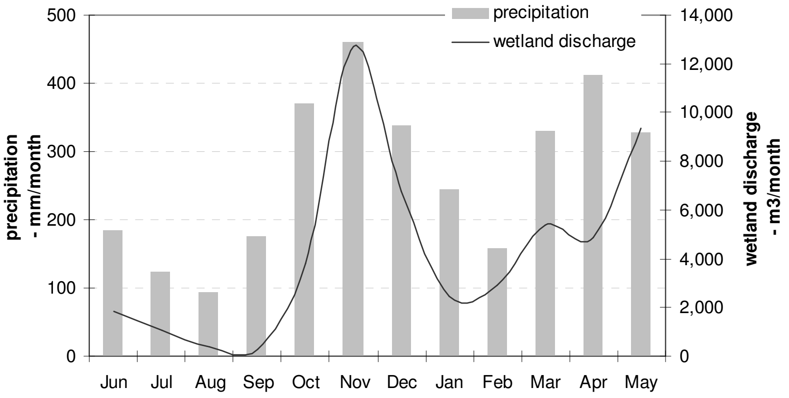
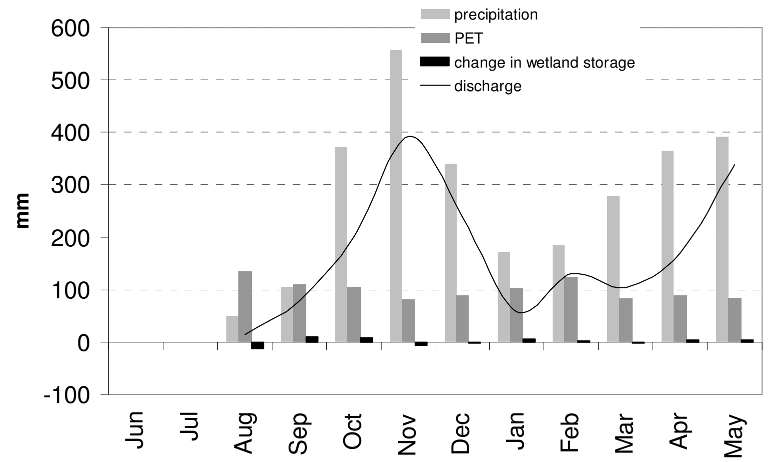
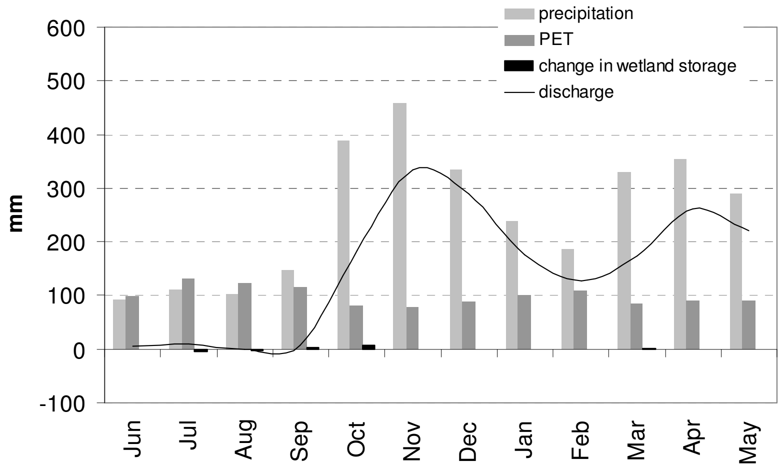


Figure 3-7 - Wetland outflow per month in relation to precipitation for: a) B1 with data for June – July 2005 and Aug 2006 – May 2007; b) B2 with data for June 2005 – May 2006 and Aug 2006 – May 2007; and c) BB with data for June – Aug 2005, Nov 2005 – Apr 2006 and July 2006 – May 2007.

a) B1 water balance components for the period August 2006 to May 2007



b) B2 water balance components for the period June 2005 to May 2007



c) BB water balance components for the period June 2005 to May 2007

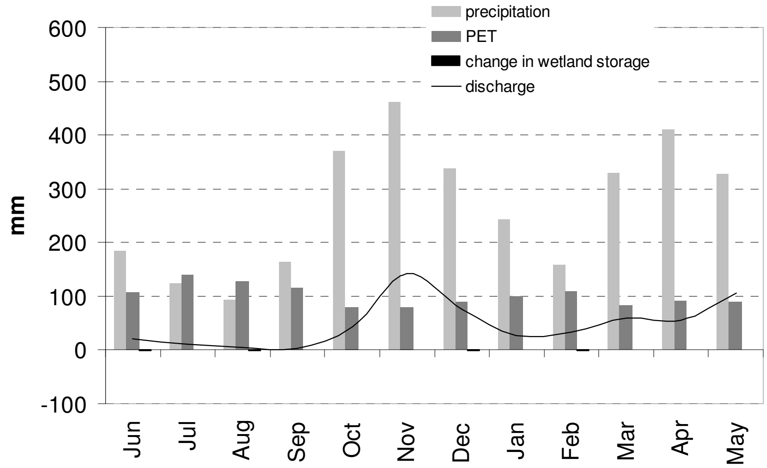
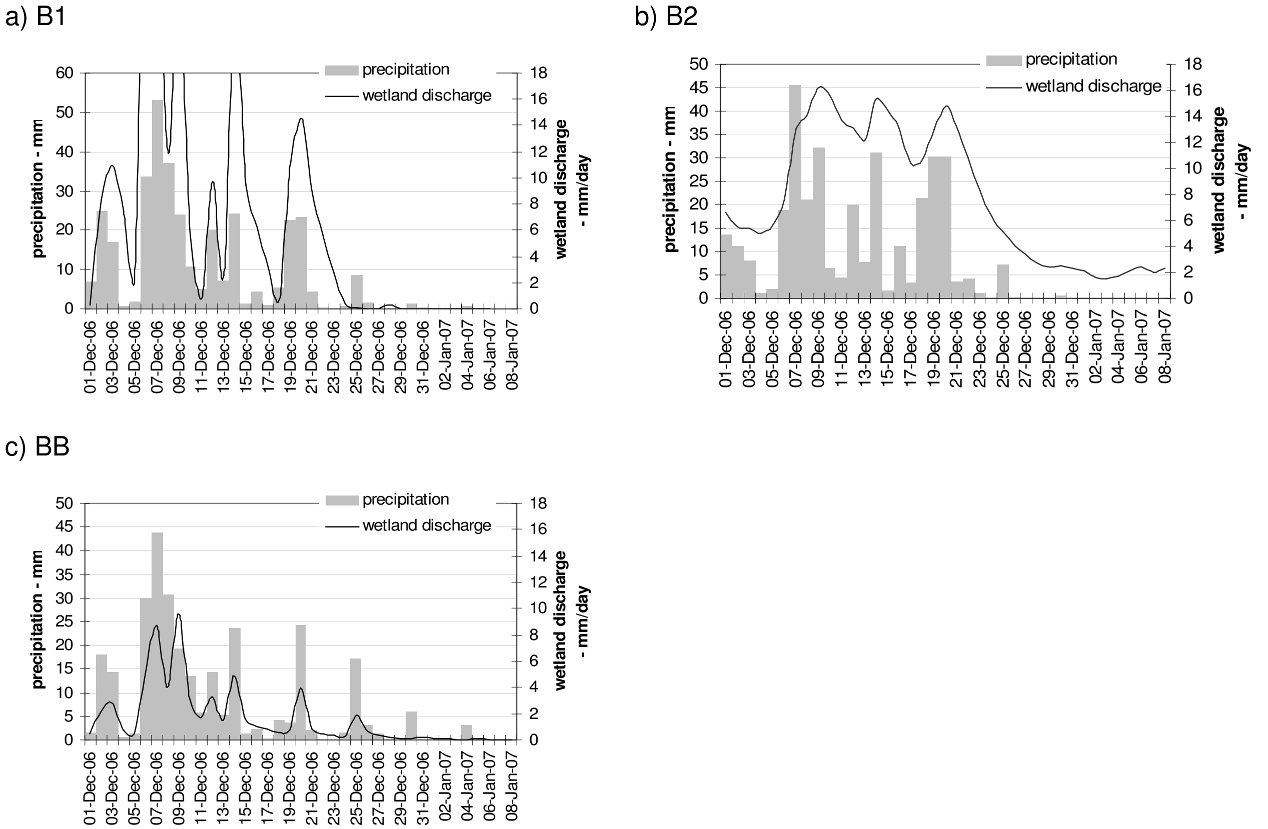


Figure 3-8 - Wetland monthly water balance components

Estimates for potential evapotranspiration and the fluctuations in wetland volume contribute to the understanding of these low flows in the dry season. The PET rates calculated are between 0.04 and 9.3 mm / day. They show that despite the high annual precipitation, the high potential evapotranspiration of the dry months creates water deficits in the three micro-catchments. Figure 3-8 shows the small contribution of the wetland storage on the discharge of the wetland micro-catchments.

Examining the transition period between the wet and the dry seasons illustrates the dynamics of flow reduction after the rains have ceased. Figure 3-9 shows the response of the wetlands on a per unit area basis (mm/day) during the last rains of the wet season (December 18th to 26th of 2006) and the 12 dry days that followed (from December 27th of 2006 to Jan. 7 of 2007). B1 returns to a negligible discharge in a matter of hours; BB drops from 0.4 mm/day (36 m^3/day) in Dec. 27th to 0.04 mm/day (3 m^3/day) in Jan. 7th with an average of 10 m^3/day for this period. B2 on the other hand, maintains a less variable flow during the rainy days and keeps a flow of around 2 mm per day which in volume terms corresponds to 58 m^3/day for the period from Dec. 27th 2006 to Jan. 7th 2007.


a) B1

b) B2

c) BB

Figure 3-9 - Wetland discharge in a transition from wet to dry season (December 18th to 25th of 2006): a) B1; b) B2; and c) BB.

This shows that despite the small contribution of the three wetlands on a volume basis (Figure 3-7), by unit area they behave differently, B2 showing a higher flow in the transition period than the other two wetlands.

3.4.2.2. Wetland yield comparison

The graphs on Figure 3-10 represent the water yield of the wetland (on the X axis) and the water yield of the catchment (on the Y axis). Water yield refers to the surface discharge of water on a weekly basis for a particular geographical unit. The data was split between the dry and the wet season and seeks to compare the three wetlands in relation to their contribution to the stream discharge by season and draw conclusions about the properties of wetlands in relation to their water yield.

One factor to consider when interpreting these graphs is the scatter. The distribution of points for B1 in both seasons is wide which provides an indication of the flashy response of the wetland to precipitation events. The three streams flow even when the wetlands are not producing surface discharge and B2 is the only wetland that does not show low flows in the wet season (less flashy).

The slope of the lines indicates the relation of the water yield of the catchment versus the wetland contributing area. A slope lower than 1 indicates that the wetland has a higher water yield than the catchment and a slope higher than 1 indicates that the catchment produces more water per unit area than the wetland micro-catchment.

BB is the only wetland that during the dry season has a water yield below the one of its corresponding catchment, although the high water yield of B1 wetland in the dry season is probably due to its flashy response to rain events, thus it does not represent a continuous water flow regime from the wetland to the stream. B2 wetland on the other hand, although dries out during part of the dry season, shows a water yield above the water yield of the overall catchment. What this analysis shows is that the characteristics of the wetlands are important in how they contribute to baseflow. One possible factor explaining the higher water yield observed from B2 wetland in the dry season is that it is a wetland with an open surface of water with no vegetation that the other 2 wetlands do not have. This might explain why the wetland has a “reservoir” type of flow, until the water level drops below the wetland surface outflow level. Only five wetlands in the study area with a total area of 0.9 ha have these properties: three in catchment BB with an area of 0.7 ha. The other two are in catchment B2 with a total area of 0.2 ha. The largest wetland with these characteristics, located in catchment BB and with an area of 0.6 ha could not be included in the study because the property owner did not permit access.

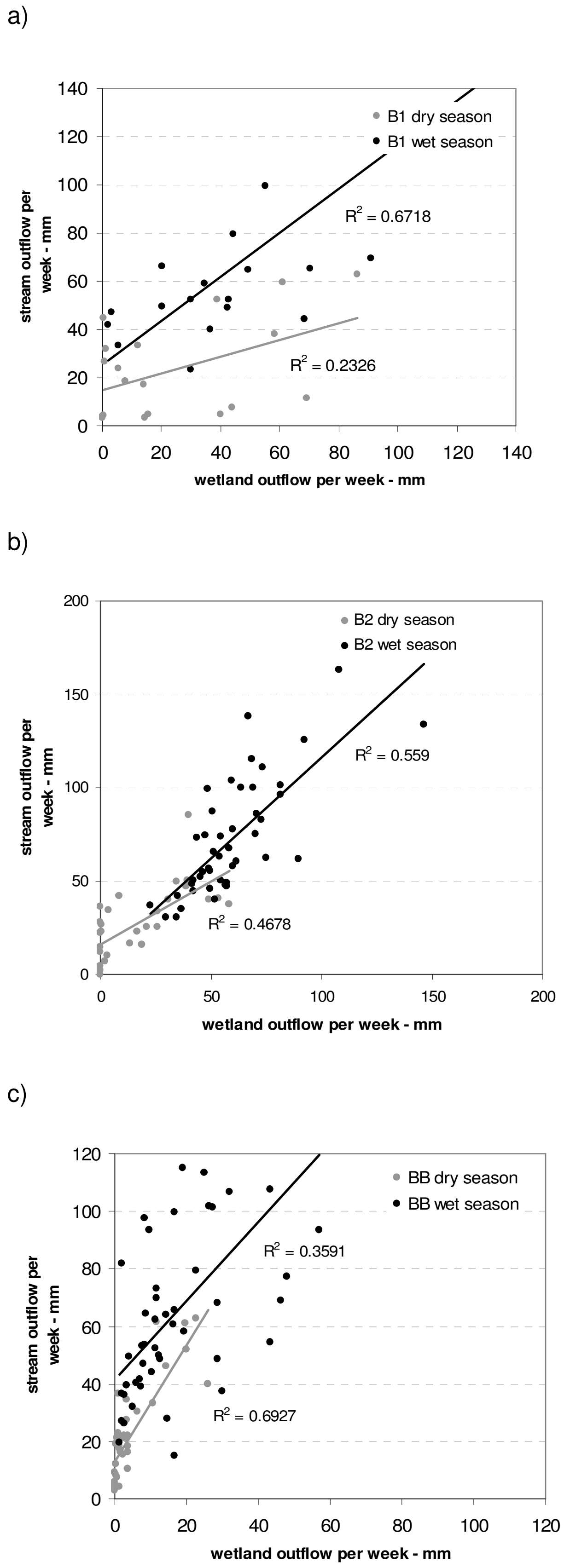


Figure 3-10 - Wetland and stream discharge: a) B1; b) B2; and c) BB

From integrating results for the monthly discharge of the three wetlands, the analysis of the transition from the wet to the dry season and the wetland-stream yield comparison, it is apparent on a per unit area basis that BB after discharging a large proportion of the water stored during the rainy season, keeps flowing at a slow rate for a longer period of time in the dry season given its flatter topography. B2 does not “burst” and maintains a relatively higher flow for a shorter period of time in the dry season, but ceases flowing once a certain level of water in the wetland is reached. This is reflected in the wetland-stream yield comparison which shows that wetland B2 is more “productive” than its host catchment during part of the dry season, while wetland BB shows significantly lower water productivity than its host catchment.

In summary, two of the three wetlands keep their surface outflow during an important part of the dry season, but with significant differences in their rates and duration. The wetland that maintains the discharge for the longest time (BB) as indicated by the flow duration curves, generates a relatively small flow in the dry season and a minor contribution to the catchment yield. The wetland that maintains a more constant flow (B2) – given by a flatter flow duration curve, does not maintain such flow as the dry season advances, but it produces a higher yield than the overall catchment while it lasts. Topographic differences and soils porosity could be the main factors explaining this different response to precipitation; and demand from evapotranspiration could be the main factor explaining low flows in the dry season.

3.4.2.3. Wetland response to rain events and discharge attenuation

The question in this section is whether the wetlands and their contributing areas store water from rain events and retain it for a period of time, and what characteristics of wetlands and events are conducive to the provision of such environmental services. Two indicators were used for this analysis: 1) the equivalent proportion of rain from an individual event that flows out of the wetland during and after the rain event (discharge coefficient); and 2) the time lags between the peak of the rain event and the peak of wetland outflow.

The total number of rainfall events analyzed was 187 for B1, 393 for B2 and 408 for BB. For each of these events the total rainfall for each event was compared with the wetland discharge for the period from when the event started until two hours after the rain ended. In all the events analysed, the amount of rain that falls on the contributing area is greater than the median amount of water that flows through the wetland surface outflow from the beginning of the event until two hours after it has stopped raining (Table 3-6). This suggests that the wetlands and their contributing areas are playing a role in dampening rain events by retaining the storm water for a period of time and releasing it after the rains end. The detailed response of each wetland by type of event is provided in Appendix 6.

Table 3-6 - Wetland event discharge and water storage

season	N	median event precipitation (mm)	Discharge coefficient	change in wetland volume per unit area (mm)
B1				
dry	47	17	28%	40
wet	140	19	28%	14
Average			28%	
B2				
dry	82	18	15%	95
wet	311	19	22%	38
Average			18%	
BB				
dry	103	19	7%	19
wet	305	18	12%	14
Average			10%	

The average of median wetland discharge per event (from the beginning of the event until two hours after the rain stopped) divided by event precipitation is used as an indicator of storm attenuation capacity of the wetlands (Table 3-6). According to this, wetland B1 has the lowest capacity (the equivalent of 28% of the rain water has flowed out of the wetland two hours after the rain has stopped), B2 has a intermediate capacity (15% and 22% in the dry and wet seasons respectively on average) and BB has the largest capacity to attenuate flows (the equivalent of 10% of rain has flowed after 2 hours after the rains ceased). These percentages are an indicator of the proportions of water volume entering and leaving the wetland contributing area during and two hours after a precipitation event. There is an important difference in flow and water storage between the dry and wet seasons. In the dry season the wetlands are not at full storage capacity. For wetlands B2 and BB the discharge from the beginning of the rain event until two hours after it stops raining, is greater in the wet seasons in comparison with the discharge in the dry seasons, which gives an idea of the water storage capacity of the wetlands and their contributing areas. For example for BB the median discharge in the dry season is 7% of the event precipitation compared with 12% in the wet season.

A more detailed assessment is provided by comparing the median values for wetland discharge versus precipitation for each event type and season (Figure 3-11). The slope of the lines indicates the level of response of the wetland to storm events. B1 is the wetland with the smallest storage capacity per unit area and therefore it allows more water to pass through the system between the beginning of the event and two hours after it has stopped raining. B2 and BB have similar slopes showing a similar water storage capacity per unit area with a slightly greater storage for B2 than for BB. A clearer signal of higher discharge in the wet season from BB was expected given its high monthly outflow rates at the end of the wet season (Figure 3-7). The lower discharge coefficient in BB might be explained by the variable degree of wetland saturation found throughout the entire wet seasons, and suggests that the “burst effect” is dependent on specific combinations of saturation and event types.

Wetland B1 has a larger area than wetland B2, and yet its discharge coefficient in the wet season is significantly higher that the observed for wetland B2. This indicates that other properties of wetlands such as soil bulk density, porosity, and organic matter content, plus the depth of the wetland might be more influential factors than wetland area determining event response.

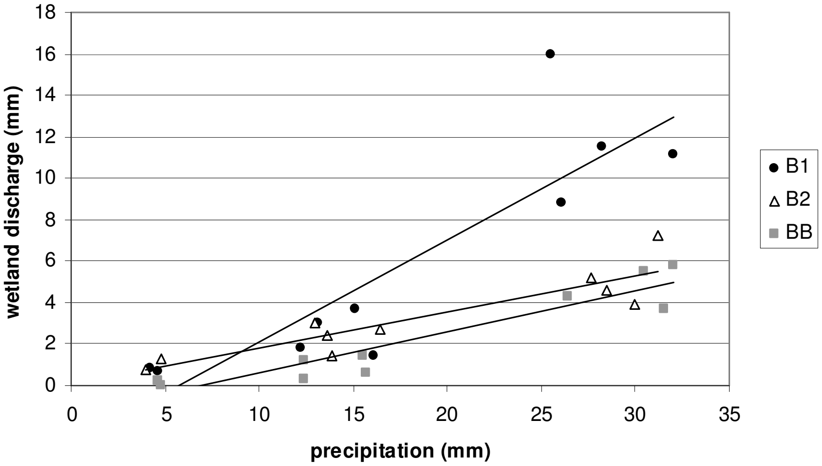


Figure 3-11 - Correlation between event precipitation and wetland outflow by event type and season

The second indicator of storm flow attenuation is the lag time between the peak rainfall of the event and the peak in wetland outflow (tlpf). The results suggest that the only wetland whose peak discharge is significantly delayed in the wet and the dry seasons is BB (Table 3-7). These results are not surprising since lag times are related to the size of the contributing areas (McGlyn et al., 2004).

Table 3-7 - Weighted average of the median lag times for the three wetlands in the wet and dry seasons.

tlpf (min)	**WB1**	**WB2**	**WBB**
wet	46	52	118
dry	53	44	90

The wetland hydrographs and corresponding hyetograph for typical events in each of the seasons and each of the wetlands show that wetland size can help explain the differences in time lags. As an example, the results of a large and intense event (type 4) in the wet season are compared in Figure 3-12 for the 3 wetlands. From Table 3-7 it is derived that BB is the only wetland that consistently yields a lag time between the wetland peak in volume and the peak in discharge, the latter always happening after the wetland has reached its maximum volume for the event. This is an indicator of the buffering effect of the wetland that holds water for a short period of time before it flows out on its way to the stream.

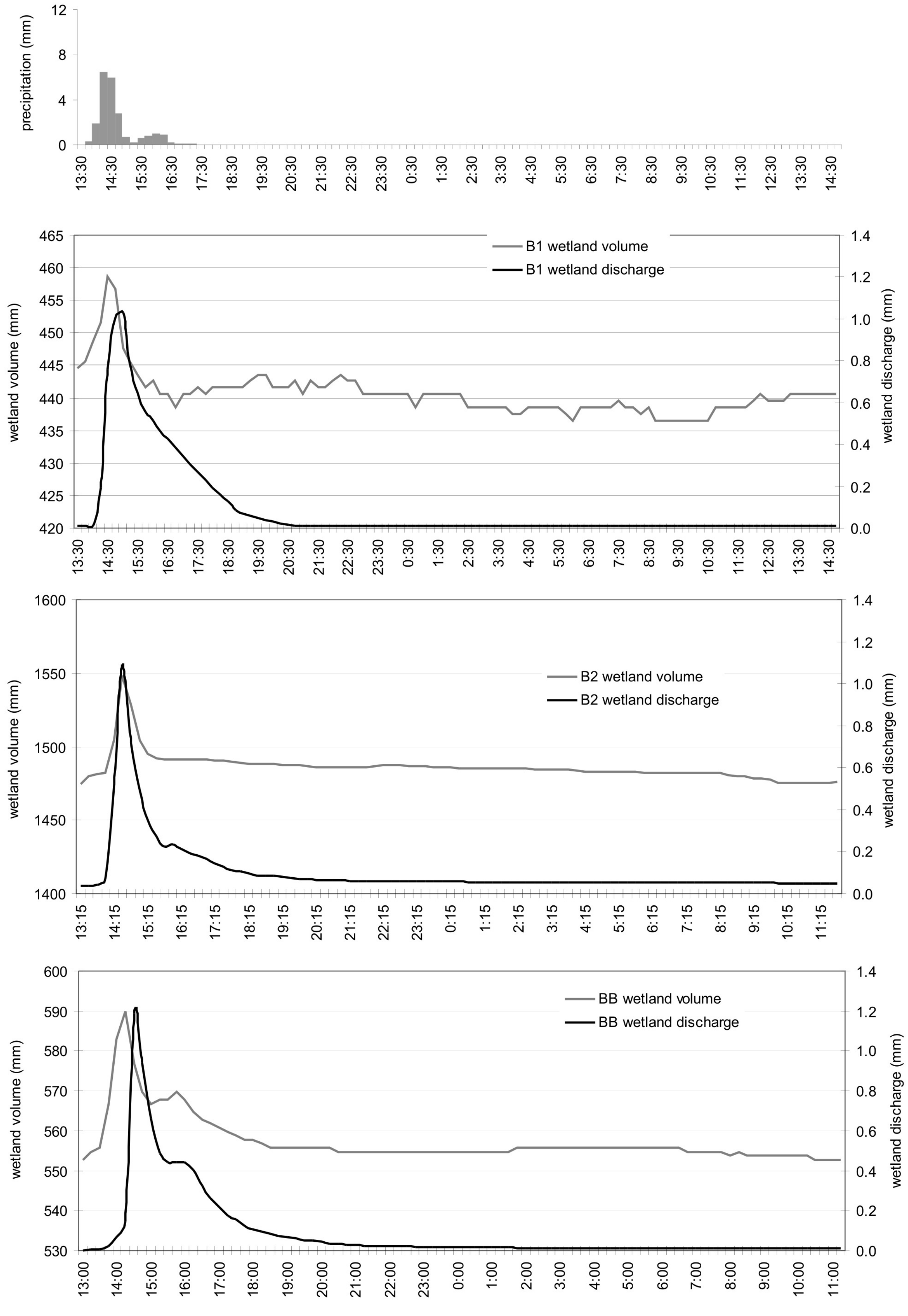


Figure 3-12 -Hydrograph and hyetograph for the 3 wetlands for an event type 4 in the wet season, Apr. 18th, 2007

In terms of storm flow attenuation, it appears that wetland size is a key factor contributing to delaying peak flows, since BB (the biggest wetland) is the only one that consistently has a lag in time between the peak in event precipitation and the peak in wetland outflow.

The characteristics of the storm (intensity and duration) combined with the antecedent rains is to a large extent what determines wetland discharge and time lags (Appendix 7); given that intense events (type 3 and 4) account for about 45% of total precipitation with intensities of over 4 mm per 15 minutes, it is hard to expect long lag times and recessions between the peak in volume and the peak in flow.

3.5. Conclusions

The three wetlands studied showed varying degrees of disturbance, according to various indicators such as the wetland plant inventory, and soil properties like organic matter content, soil porosity and water temperature. B1 can be described as a highly impacted wetland, with lower soil porosity, lower organic matter content, significantly higher water temperature, and a reduced number of wetland plants in comparison to the other two studied wetlands. B2 can be described as a dynamic wetland, that shows large fluctuations in water level due to its steep topography, large contributing area and high porosity, and despite being the smallest wetland in terms of area, it hosts a larger number of plants than B1; this wetland also has the highest values of organic matter at lower depths. BB is the wetland that shows the smallest water level fluctuation, and the largest number of wetland plants, factors related to its larger area; it has the highest percentage of organic matter content at shallow depths, compatible with the more constant saturation conditions (less water level fluctuation). Wetland BB is a relatively old wetland, accumulating organic material for over 5,000 years and showing decomposition rates of approximately 7 cm per 100 years which is higher than the rate of accumulation for temperate and boreal wetlands.

A hydrological analysis of three headwater wetland micro-catchments examined what influence these wetland systems have on flow regulation in their respective catchments. Wetlands contribute to baseflow at a lower rate than the overall catchment on a per unit area basis and their contribution to dry season flows is very small in terms of volume of water. Evapotranspiration is a large cause of water withdrawals from wetlands in the dry season. The dry season flow of B2 and its characteristics show that a wetland with open water and a surface outflow can behave as a reservoir at least for part of the dry season. Although its dry season flow is negligible, probably as a result of its small size.

In terms of the dampening of storm events, the responses of the three wetlands are dependent on the previous precipitation conditions that determine the amount of water in the wetland and the contributing area. In general terms only BB, the wetland with an area of over 6,500 square meters produces lags between the peak of a rain event and the peak in flow of two hours in the wet season and 1.5 hours in the dry season. B1 and B2 present lags of less than one hour for peak in flow. The question remains whether these lag times are significant enough to ameliorate downstream flows and prevent floods. A comparison of the wetland micro-catchment scale to the larger catchment scale is necessary to quantify the differences in time lags and see whether the wetlands increase or decrease the lags at the catchment scale.

The characteristics of wetlands in terms of soil porosity, bulk density, soil organic matter content, and wetlands depth, which can be related to the degree of disturbance of a wetland ecosystem, influence the water volume response of wetlands to rain events, more than the wetland size. This was demonstrated by the discharge coefficients of the three wetlands.

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4. Land use, wetlands and water flows in small headwater catchments of the Andes[1]

4.1. Introduction

Most of the major rivers of the world have their headwaters in highlands and more than half of humanity relies on the freshwater that accumulates in mountain areas. Although mountain headwater catchments constitute a relatively small proportion of river basins, most of the river flow downstream originates in mountains, the proportion depending on the season (Viviroli et al., 2007). Globally it is estimated that 32% of the global discharge comes from mountains (Meybeck et al., 2001), and regionally it can be as much as 95% (Liniger et al., 1998).

The Andean Mountains are the world's longest range of linear continuous high mountains and the second highest after the Himalayas. In Colombia, the Andes split into three branches with a south-north direction, giving origin to two intermountain valleys. The three cordilleras with maximum altitude of 5000 m provide a geographical variability that combined with climatic factors and geological heterogeneity, create a high diversity of ecosystems and species (Murgueitio and Calle, 1999).

In Colombia as in many parts of the tropics, mountains are preferred areas for human habitation because of their moderate climate. Over 66% of the Colombian population is located in areas above 500 m, which corresponds to the Andean region, and makes up only 24.5% of the country (Etter and van Wyngaarden, 2000). More than 80% of the Colombian population obtains its water from small sources – streams, creeks and small rivers. It is estimated that there are around 700,000 catchments with areas of less than 10 km^2 in the country. Only 15% of these small catchments are located in the Andean region (IDEAM, 2000), therefore the pressure on these catchments is high. Despite the fact that precipitation is higher in the mountains, the population depending on water coming from the mountains is recurrently subject to scarcity and to use restriction of the resource. The water discharge from the Andean region of Colombia is estimated at 580,000 million m^3 for a normal year and decreases by 30% during a dry year. According to the National Institute for Natural Resources, the highest pressure on water resources in the country is concentrated in the Andean region, particularly in the medium to high portions of the Cauca and Magdalena basins. For scenarios of dry years, 66% and 69% of the population could be under high risk of water scarcity for the years 2015 and 2025 respectively (IDEAM, 1998).

In Colombia, one of the main factors that have influenced the transformation of the Andean landscape was the introduction of cattle by the Spaniards in the 16th century. Large areas of sloping terrain were transformed into extensive grazing lands with negative effects, e.g. landscape homogenization (Etter and van Wyngaarden, 2000), erosion (Murgueitio, 2003), and loss of the capacity of watersheds to regulate hydrological flows. Headwater streams of the Andes have highly modified flows

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[1] A version of this chapter will be submitted for publication
Roa-García, C., Schreier, H., Land use, wetlands and water flows in small headwater catchments of the Andes.

due to the development and use of water resources, and the alteration of the water regulation capacity of soils (Buytaert, et al., 2005, Buytaert et al., 2006, Diaz, 2006).

Additionally, within the next decades, effects of climate change and population growth are expected to worsen water resources supply significantly, particularly through altered discharge patterns from mountains (Messerli et al., 2004) and increasing demand for food production. Land use and water management activities can significantly affect the baseflow regime.

Limited knowledge about the fluctuation in stream discharge and the rapid change occurring in ecosystems associated with climate and land use changes impairs the decision making processes to manage water. Taking into account the increasing water scarcity in many regions, especially for irrigation and food production, today's state of knowledge in mountain hydrology makes sustainable water management and an assessment of vulnerability quite difficult (Messerli et al., 2004).

Knowledge about the hydrology of small tropical mountain headwater catchments is still limited and myths about the role of ecosystems in “producing” water are prevalent. This research provides an understanding of the influence that land use differences have on the hydrological behavior of small headwater catchments of the tropical Andean mountains. The study was done in the municipality of Filandia in the western side of the central branch of the Colombian Andes. This municipality relies on the water flows from three small catchments occupied by six farms dedicated to extensive cattle ranching and covered with different composition of vegetation. The catchments are known in the region for holding a significant number of wetlands that are believed to be important in the contribution of water flows especially in the dry season when water flows are significantly reduced. Through this study wetlands were found to occupy 6% of the area of one of the three catchments and between 1% and 2% of the other two catchments, areas significantly smaller area than previously thought. The goal of this study is to compare the hydrological behavior of the three catchments and link them to differences in the land use composition. This study will try to identify the influence of the existing wetlands on catchment hydrology.

4.2. Study site

The catchments are located in Filandia (4.67º N, 75.63 º W) at 2,000 – 2,200 m of elevation, in the coffee growing region of Colombia, on the western side of the central branch of the Andes and drain to the Cauca River, which flows north to the Atlantic Ocean. The micro catchments are called Barro Blanco (White Mud in Spanish referring to the ash layer seen in parts of the catchment) and Bolillos (the name of an endemic palm tree that grows in the area). For this study the Bolillos catchment was divided in two smaller units called Bolillos 1 and Bolillos 2. For convenience the catchments are called BB, B1 and B2 respectively. Most of the land in the three micro-catchments is dedicated to extensive cattle rearing for different purposes including milk production, meat and bulls sold for bullfighting. The decline in coffee prices since the mid 1990s and the increase in cattle and meat prices in the last few years have stimulated the expansion and intensification of cattle ranching in the three catchments.

The municipality of Filandia, a town of approximately 15,000 people, obtains all the water for its domestic, agricultural, commercial and recreational use, from these 3 streams. However, despite the fact that average annual precipitation in the region recorded since 1972 has been approximately 2,990 mm, the municipality faces recurrent water shortages during the dry season.

The high precipitation and the hummocky topography of the three catchments have been conducive to the formation of wetlands. A recent paleoclimatic study found that one of these wetlands has an age of over 5,000 years and its layers store a good climate record of the recent Holocene (Muñoz Uribe, P., 2007). These wetlands are believed to be an important source of water during the dry months.

The topography has been described as hummocky (Guarín, et al., 2006) and the parent material of soils are fluvio-volcanic sediments, mostly clays of uniform size. There is a volcanic ash layer, which can reach tens of meters in thickness at some locations. The layer is characterized by very low hydraulic conductivity constituting an aquiclude, which contributes to the formation of wetlands, as it limits water percolation and maintains a high water table. Soils formed on these sediments are classified as Andisols (Acrudoxic Hapludans) (IGAC, 1996). After Histosols, Andisols are the soils with the highest organic matter content which, in combination with their high content of allophanes and imogolite, result in light soils with high water holding capacity.

Central Colombia and the western Andean cordillera experience a bi-modal annual precipitation cycle where rainfall peaks during April–May and October–November, and is low during December–February and June–August. This is caused by the double passage of the Inter-Tropical Convergence Zones (ITCZ). The seasonal strengthening of the Chocó Jet (September–November) and weakening (February–March), partially explains why the October–November rainy season is more intense than that of April–May over central and western Colombia (Poveda et al., 2006).

4.3. Methods

In order to compare the hydrological behavior of the three catchments and relate it to their land use characteristics, the analysis and monitoring program was divided into two components: 1) land use differences in the three catchments, and characteristics of soils in relation to the water retention-release processes for each land use type; and 2) hydrological response of the three catchments at various time scales (monthly and season fluctuations of discharge and storm response). Once the hydrological differences between the three catchments were established for low flows and storm response, these were linked to the previously described traits of each of the catchments. Low flows were analyzed through flow duration curves (Smakhtin, 2001) and water yields at different time scales; and storm flows were analyzed using hydrographs, time lags differences, and the linear reservoir concept (Dingman, 1994).

As part of the characterization of soil-water dynamics in the catchments, three processes were quantified: surface and sub-surface runoff processes occurring in grasslands; and infiltration rates of water in soils under different land use types. The rates of these processes were measured to contribute to explain the hydrological processes taking place at the catchment scale.

The study was designed as a comparative-catchment study, similar to paired catchment studies that are used to compare two catchments with similar characteristics in terms of slope, aspect, soils, area, climate and vegetation located adjacent or in close proximity to each other (Brown, et al., 2005). The principle of a comparative-catchment study is the selection of, in this case 3 catchments, as similar as possible (in particular, in terms of size, morphology, geology and climatic forcing) and monitor them jointly during a given time period, to understand their differences (Andreassian, 2004). Since the major conversions of land use in the catchments occurred more than 10 years ago, it is assumed that the catchments are stable and the differences in hydrological behavior correspond mainly to differences in land use. The catchments were monitored from May 2005 until May 2007.

4.3.1. Land use mapping and wetland inventory

A land use map was developed using a 2003 satellite QUICK BIRD image with a resolution of 0.6 meters combined with field examination using a GPS (Navman). The field mapping was subsequently transferred to ArcGIS© (ESRI) for spatial analysis. Parallel to the land use map, a field based wetland inventory was undertaken to classify wetlands according to whether: they were temporary / permanent, fenced / not fenced, they had a surface outflow, they had a water source in addition to rain, and they had a portion of their total area as open water or a non vegetated surface water area. The inventory and classification of wetlands was used to identify factors that could potentially be linked to the hydrological behavior of the wetlands and their influence on their catchments. Wetlands that had a non vegetated surface water area, were classified as wetlands with open water.

4.3.2. Precipitation, wetland and stream flow

Three data logging rain gauges were installed in the three catchments, to measure precipitation over the catchments. These rain gauges were installed at elevations between 2,100 and 2,135 meters and recorded precipitation from October 2004 until May 2007. The seasons were separated using weekly precipitation. The dry season in 2006 runs from the end of June until the second week of October; the wet season of 2006 goes from the second week of October until the third week of December; and the first or little dry season of 2007 goes from end of December 2006 until the first week of March 2007. Events were classified according to intensity and duration into five categories described in Appendix 3.

For the continuous measurement of water level in the streams, three AquiStar PT2X Smart Sensors™ (Instrumentation Northwest, Inc., Kirkland, WA) were used. These devices are submersible pressure/temperature sensors and data loggers combined in one unit that provides the net pressure (referenced to atmospheric pressure) with an accuracy of ± 2 millimetres for pressure (Instrumentation Northwest, Inc., 2003). Water level was recorded every 15 minutes from June 2005 until May 2007.

To convert water level into amount of water flowing in the three streams, a stage-discharge relationship was determined for each site to relate water level in the stream channel, with water flow. This was done taking water flow measurements in a wide range of water levels using a current meter built by OTT© – Messtechnik GmbH & Co. (Kempten, Germany). These water level data series were converted into flow measurements with stage-discharge relations by 62, 44 and 50 discharge measurements for catchments B1, B2 and BB respectively. Stage-discharge curves are provided in Appendix 8. The data series collected for streams were analyzed using IDL©, and used to build flow duration curves – FDC, calculate water yields for different time scales, lag times, and build hydrographs for event analysis.

The surface water outflow of the three chosen wetlands was monitored through continuous measurements of water level using Odyssey® capacitive water level recorders (Dataflow Systems, New Zealand, 2002). Water level was recorded every 15 minutes from June 2005 until May 2007 at the three wetland outflows. Flow measurements were taken using the salt dilution method (Moore, 2004). This method is considered accurate for small streams with irregular channels (Dingman, 2002). Stage-discharge relationships were developed using 15, 22 and 14 discharge measurements for wetlands B1, B2 and BB respectively.

Potential evapotranspiration was calculated using the Penamn combination equation taken from Dunne and Leopold (1978), with daily data (Appendix 2).

4.3.3. Soil moisture curves, porosity, and infiltration rates

Soil moisture retention curves were built based on 24 soil samples corresponding to the three major land use types (grasslands, riparian forests and plantation forests) and analyzed for water retention-release capacity using pressure plates (Klute, 1986) at the soils laboratory of the International Center for Tropical Agriculture in Colombia. The results were compared with the typical values for the soil moisture retention curves of clay, silt and loam by Brady & Weil (2002).

Total soil porosity was calculated based on soil particle density. 11 samples were taken to measure soil particle density of soils under grasslands, and the same number of samples for forest soils using the Pycnometer method (Blake and Hartge, 2006).

Differences in water storage were calculated according to land use and season based on soil moisture measurements taken using a reflectometry sensor, HydroSense Soil Water Content Measurement System™ (manufactured by Campbel Scientific, Inc., Edmonton, Al, Canada). This is a portable device that displays the volumetric water content in percentage with a resolution of 1% and an accuracy of ±3.0%. Measurements were made by inserting the 20 cm probe rods into the soil. Measurements were taken weekly at chosen sites for the major three land use types: grasslands, riparian and natural forests, and plantation forest, from June 2006 until June 2007. In B1 three riparian/natural forests sites were monitored, one plantation forest site and three grassland sites. In B2, three riparian forest and three grassland sites were monitored. In BB, six riparian/natural forests, two plantation forest and seven grassland sites were monitored.

Water infiltration rates were determined for soils under grass using a handheld minidisk infiltrometer™ (manufactured by Decagon Devices, Inc., Pullman, WA, USA). Measurements were done at 15 sites for grassland soils.

4.3.4. Surface and sub-surface flow

Surface runoff was quantified using a runoff plot connected to a barrel of half a cubic meter volume. The barrel was buried at the lower end of a 10 meters by 10 meters square area of pasture delimited by tin sheets buried 20 centimeters from the surface. Measurements were taken daily since November 2005 until May 2007.

Sub-surface lateral and vertical flow of water in the soil was determined in the field using a vertical trench 2 meters long and 1.5 meters deep. The vertical surface was covered by a permeable fabric and a perforated hose was placed at the bottom of the trench under a plastic sheet that surrounded it and covered the permeable fabric. The three m long hose was connected to a barrel located at a lower level than the levelled hose, to collect and measure the water coming out of the trench. Measurements were taken daily since May 2006 until May 2007.

4.3.5. Event response analysis

The response of catchments to the different types of events was analyzed using the time lags between the peak in rain and the peak in flow - tlpf. The calculation of these lag times for all rain events as well as the analysis of the data series collected were analyzed using Interactive Data Language - IDL©.

Events were also analyzed using the linear reservoir model which was applied to 15 rain events chosen based on the spatial heterogeneity of precipitation in the 3 catchments. The linear reservoir equation describes discharge (Q) as a variable dependent on the water stored in a catchment (S) (Dingman,1994).

$$Q = k * S$$

$$\delta S / \delta t = -Q$$

$$\ln Q = \ln Q_o - t / T$$

Where Q is the outflow, S is the stored amount of water, t the time and k is a rate constant which is the inverse of the time constant T and is an index of the speed at which a reservoir drains. T indicates the buffering capacity of a reservoir or the “slowness” of the water release. As such it is a good means for estimating the water buffering capacity of the water storage reservoir, S (Buytaert et al., 2004).

For each of the events, three different Ts were calculated by dividing the corresponding hydrograph into three slopes and using the linear reservoir equation to calculate T for each section. T1 (fast), T2 (moderate) and T3 (slow) represent the time in hours that each of the theoretical reservoirs takes to drain out of the catchments.

4.4. Results and discussion

4.4.1. Land use

The catchments differ in size and land use. BB is the smallest catchment (0.6 km^2), but has the highest proportion of wetland area. B2 is the largest catchment (1.7 km^2), with the highest proportion of grasslands. And B1 (1.5 km^2), is slightly smaller than B2 but has a large proportion of natural and riparian forest (Table 4-1).

Table 4-1 - Land use areas per catchment

	B1		**B2**		**BB**	
	ha	**%**	**ha**	**%**	**ha**	**%**
Riparian and natural forest	81.2	51	48.9	27	15.6	25
Plantation forest	27.7	17	1.9	1	3.3	5
Grasslands	47.7	30	123.6	69	38.7	62
Wetlands	0.8	1	2.7	1	3.8	6
Roads and buildings	1.2	1	2.1	1	0.6	1
Total area	158.6	100	179.1	100	61.9	100

Figure 4-1 shows the concentration of natural and riparian forests in B1, and of grasslands in B2 and BB. It is also evident that wetlands occupy a larger percentage (6%) of the catchment area in BB.

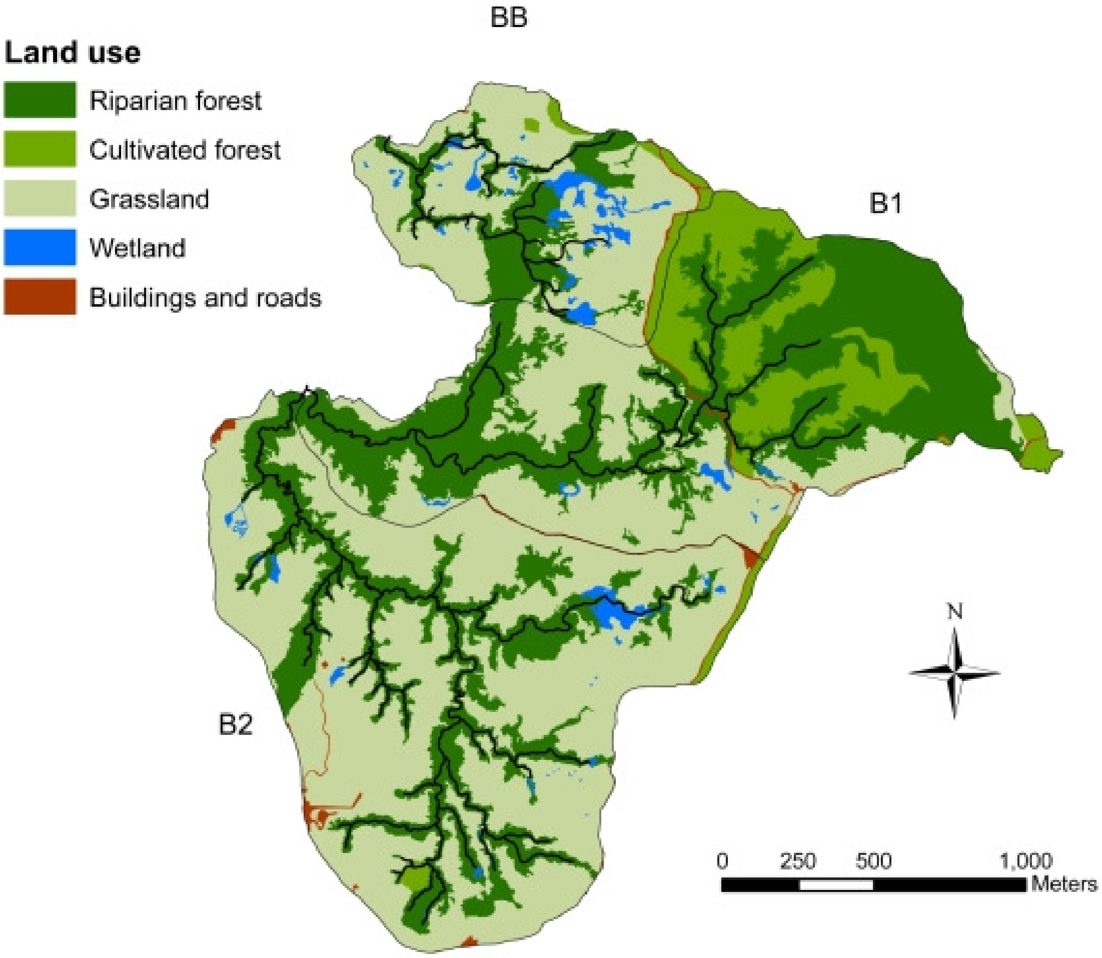


Figure 4-1 - Land use map for the 3 micro-catchments

As an indicator of the differences in topography, Table 4-2 shows the altitude of the highest point in each catchment (maximum elevation) and the altitude at the catchment drainage point (minimum elevation).

Table 4-2 - Maximum and minimum elevation for each catchment

	Maximum altitude – meters	Minimum altitude – meters	Difference	Difference/distance to outflow point
B1	2,211	1,999	212	10%
B2	2,130	1,999	131	7%
BB	2,148	2,035	113	13%

The differences in elevation vary relative to the distance from the drainage point to the most distant point in the catchment. As indicated by the slope, topography does not appear to be a major factor that would significantly affect discharge.

4.4.2. Wetland inventory

The results of the wetland inventory (Table 4-3) show that catchment BB has the largest area of wetlands totaling 3.8 hectares or 6.1% of the catchment area. For catchments B1 and B2 the area of wetlands corresponds to 0.5% and 1.5% of the catchment area respectively.

Table 4-3 - Summary of wetland inventory

Catchment	Number of wetlands	Area of wetlands (ha)	Total catchment area (ha)	% area of wetlands	Number of wetlands with open water	Area of wetlands with open water (ha)
B1	8	0.8	159	0.5%	0	0
B2	22	2.6	179	1.5%	2	0.2
BB	22	3.8	62	6.1%	3	0.7
Total	52	7.2	400	2.0%	5	0.9

The areas in Table 4-3 represent the actual wetland area and do not include the contributing area that surrounds the wetland which constitutes the wetland micro-catchment. According to a previous hydrologic study of these headwaters, the area of wetlands was 68 ha for BB and 86 ha for B1 and B2 representing 43% and 11% of the catchment area respectively. This overestimation of the wetland area has led to the belief among municipality officials and the environmental department, that wetlands are the major water reservoirs of the catchments (Saenz, 2001).

4.4.3. Soil moisture

Soil water content is relatively high in the three catchments in the dominant land uses most of the year. The average percentages of volumetric soil moisture content are shown in Table 4-4. This data shows the variation between the dry and wet seasons for the three types of land use; there is no significant difference between riparian/natural forest and grasslands, but reduced soil moisture content under plantation forests in all seasons.

Table 4-4 - Average values of soil volumetric moisture content by catchment, land use type and season

	B1	**B2**	**BB**
Riparian and natural forest			
dry season 2006	55%	45%	56%
wet season 2006	67%	63%	63%
little dry season 2007	58%	57%	59%
Average	**60%**	**55%**	**59%**
Grassland			
dry season 2006	58%	49%	56%
wet season 2006	65%	60%	63%
little dry season 2007	55%	53%	57%
Average	**59%**	**54%**	**59%**
plantation forest			
dry season 2006	47%		47%
wet season 2006	52%		56%
little dry season 2007	46%		51%
Average	**48%**		**51%**

Despite the low bulk density values of the soil of three land use types (typical of Andisols which in general range between 0.6 and 0.8 g/cm^3), as seen in Table 4-5, K_{sat} - saturated hydraulic conductivity rates for 15 surface grassland sites ranged between 40 and 400 mm/hr which are typical rates for semi pervious materials (Bear, 1972) which relates to Hortonian overland flow during storm events.

Table 4-5 - Bulk and particle density, total porosity and available water by land use type

	n	**Bulk density (g/cm3)**	**Particle density (g/cm3)**	**Total porosity %**	**Field capacity (%)**	**Permanent wilting point (%)**	**Available water (%) ($\theta_{fc} - \theta_{wp}$)**
Riparian and natural forest	10	0,6	2,3	76	61	53	7
Grassland	11	0,7	2,0	71	60	52	8
Plantation forest	2	0,7	2,3	70	64	59	6

The comparison of soil moisture retention curves of the three land use types of the study site with the typical curves for clay, loam and sand (4-2), shows that despite the large water storage capacity of the soils, they tend to hold water, reducing its movement. This is a result of the degree of soil development, soil structure, soil texture, parent material, organic matter content, biological activity and soil management (Cassel and Lal, 1992) and contributes to low infiltration rates. More importantly this characteristic makes these soils poor sources to release water in the dry season.

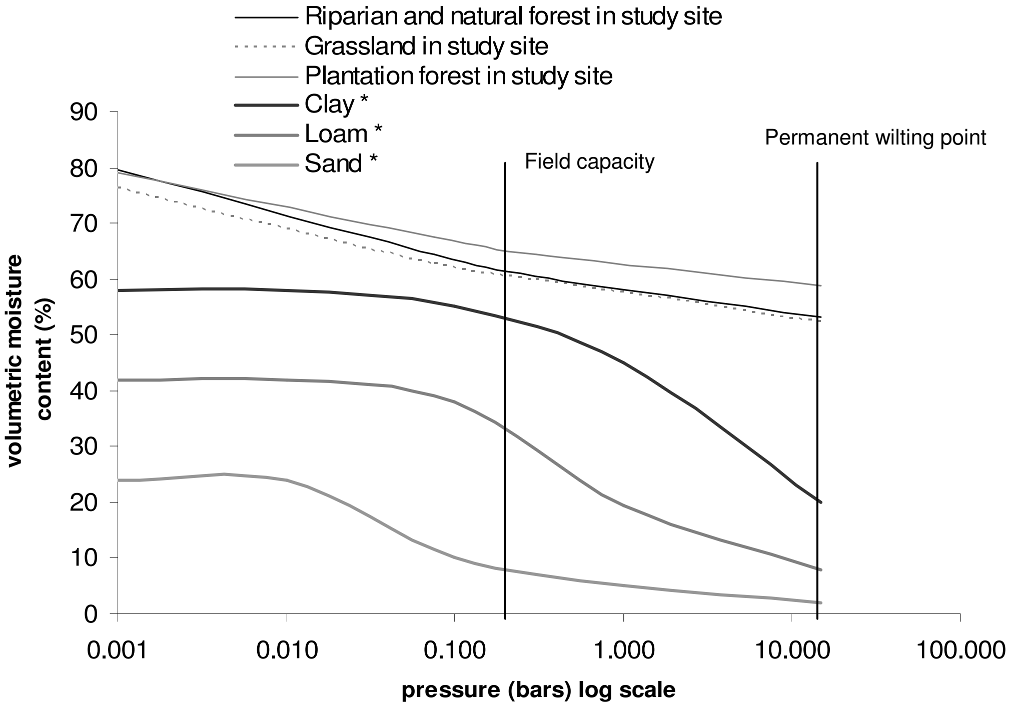


Figure 4-2 - Soil moisture retention curves. * Average values for typical soils (Brady & Weil, 2002).

To further illustrate this characteristic of the soils, a storage-release coefficient was calculated dividing the soil moisture content at field capacity by the soil moisture content at permanent wilting point. The higher the number, the higher the proportion of water held in the soil that can be released. The values obtained are between 1.3 and 1.5 for the soils in the study site and between 2.1 and 8 for the typical (clay – loam – sand soils). This indicated that despite the high water holding capacity of the studied catchments soils, they do not release it, therefore the proportion of water that can flow into the stream channels is small.

4.4.4. Surface and sub-surface flow

Surface and sub-surface runoff are processes that could contribute to explain the movement of water from contributing areas to the streams within a catchment. Daily surface runoff measurements are shown in Table 4-6 classified according to the amount of precipitation fallen on the previous 24 hours.

Table 4-6 - Surface runoff on grassland

Groups by runoff amount	>= 5 mm	5 > X >= 2	< 2
N	29	44	56
Median runoff – mm	6	4	1
1 previous day precipitation - mm	28	20	11
2 previous day precipitation - mm	46	31	21
3 previous day precipitation - mm	59	45	29
Max 15 min intensity - mm	6	5	5
% runoff over previous day precip.	23%	20%	9%

According to this data, the catchment with the highest percentage of area in grassland (B2) would have a larger volume of surface runoff occurring during storm events and flowing into the stream channel, increasing the total volume of water flowing into the stream either through a push effect of water in the riparian area, through preferred pathways, or both.

The comparison between precipitation and the data obtained for sub-surface runoff in the hillslope plot shows that the average daily precipitation required to produce a sub-surface runoff equivalent to 0.1 mm is 15 mm per day when preceded by rainy days. On average precipitation in the previous 2 days of 29 mm and of the previous 3 days of 48 mm is required to produce measurable sub-surface flows. The maximum sub-surface flow measured between Nov 15th 2005 and March 10th 2007 occurred on Nov. 12th 2006 and was 7.8 mm associated with a precipitation of 57 mm. This indicates that subsurface lateral and vertical flow is minimal during periods of no rain and that during the dry season the main processes contributing to stream base flow likely occur in the vicinity of the streams. This coincides with observations of the discharge process in catchments in New Zealand, where runoff was found to be generated mainly in the riparian zones of small catchments and transferred downstream through the channel network to the catchment outlet (McGlynn and McDonnell, 2003).

4.4.5. Relationships between forests, wetlands and discharge

For many years, it was believed that the presence of forests aided in the supply of relatively constant water flows from catchments, but an increasing number of studies show the effect of forests on reducing catchment discharge. To understand the dynamic effect of forests on the hydrology of headwater catchments it is useful to distinguish between the effect of forests on total water yield and the seasonal distribution of flows (Bruijnzeel, 1989).

The mean, the median and maximum discharge of the streams shown in Table 4-7 are proportional to the catchment sizes, but the minimum flows are not. Despite B2 being the largest catchment, its minimum flow is significantly lower than the minimum flows of the other streams.

Table 4-7 - Daily flows for each of the streams for the period May 11th 2005 to May 28th 2007

m^3/day	**B1**	**B2**	**BB**
Mean	11,239	13,276	4,006
Median	9,139	10,627	2,678
Min.	384	13	120
Max.	67,441	85,871	25,853

The total water yield for each of the catchments is given in Figure 4-3. These values show the highest water yield in the catchment with the lowest forest coverage (B2) and the lowest water yield in the catchment with the highest area of wetlands (BB). B1 has 24% more area in forests than B2, which could be related to its smaller annual water yield. Rather than the effect of the reduction in evapotranspiration, as the main driver for the increase in annual flows after forest clearing, which has been found to be the main factor in temperate areas (Bosch and Hewlett, 1982), in the tropics it appears to be the reduced infiltration capacity of the soil. According to studies by Bruijnzeel (1988, 2004), if infiltration rates after forest removal decrease to the extent that the amount of water leaving an area as quick flow exceeds the gain in baseflow associated with decreased evapotranspiration, then dry season flows will be reduced. Paired catchment studies have found that changes in land use, that are less than 20% of the catchment area, do not produce detectable changes in streamflow in small catchments (Bosch and Hewlett, 1982); however given that the percentages of area in wetlands is the biggest difference between B2 and BB, it is considered a possible explanation for the difference in water yield between the two catchments.

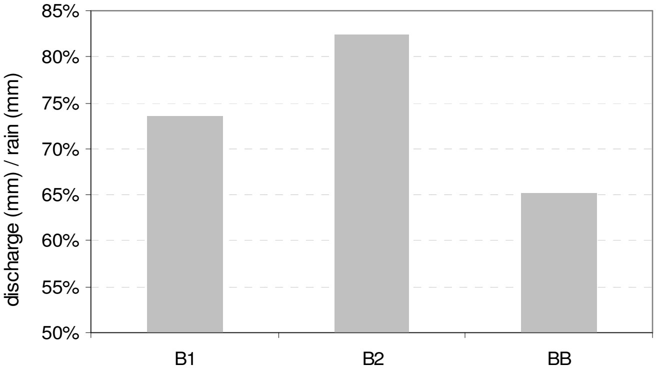


Figure 4-3 - Annual water yields for the studied catchments

The seasonal distribution of flow shows no significant differences between the three catchments during the dry months (Figure 4-4), but large differences during the wet months. B2 shows a higher proportion of discharge in relation to the precipitation in comparison with the other two catchments.

The monthly water yield observed from B2 catchment compared to B1's suggests that a reduced water holding capacity due to a smaller area in forests, combined with a predominantly intense and short rainstorm pattern, is reducing the recharge of B2 (grassland dominated catchment) for baseflow maintenance and producing higher peak flows.

This is supported by the data collected on surface runoff which indicates that roughly 10% of precipitation on grassland does not infiltrate into the soil but becomes surface runoff. The occurrence of surface runoff depends on antecedent precipitation and the max intensity of the event, as shown in Table 4-6.

The excess discharge in the wet season combined with a smaller discharge in the dry season due to the reduced water holding capacity of catchment B2, supports the "infiltration trade-off" hypothesis. This hypothesis explains the more pronounced storm discharge during the rainy season that can seriously impair the recharging of the soil and groundwater reserves feeding springs and maintaining baseflow, through reduced rainfall infiltration in cleared areas due to either continued exposure of bare soil to intense rainfall after forest clearance, or compaction of topsoil by machinery, or overgrazing, the gradual disappearance of soil faunal activity or the increases of impervious surfaces (Bruijnzeel, 2004).

The relative areas in forest in B2 and BB are very similar – 27% and 25% respectively; but their water yield (total annual mm of discharge / total annual mm of precipitation) is different by 17%. Given that factors such as catchments steepness, geology and soil depth (which influence the residence time of water in the catchment) are fairly similar for the 3 neighboring catchments, the question to ask is whether a difference of 4% of area in wetlands could explain this difference in annual water yield. The monthly distribution of flow in relation to precipitation (Figure 4-5) illustrates the differences in runoff in the wet season. B1 and BB seem to have a smaller runoff during the wet months in comparison with B2, except in Nov. 2006, the wettest month recorded when BB had a higher runoff. The monthly runoff does not illustrate the fluctuations of stream discharge in the dry season, which happen at a finer time scale. A comparison of the daily flows through flow duration curves will help to understand better the effect of wetlands in the catchment discharge.

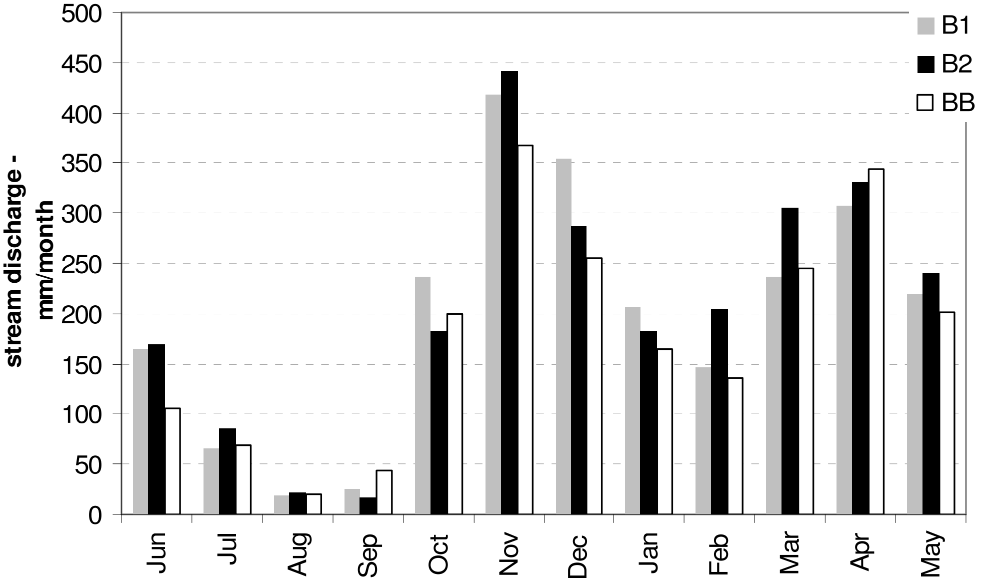


Figure 4-4 - Stream discharge in mm/month for the three studied catchments

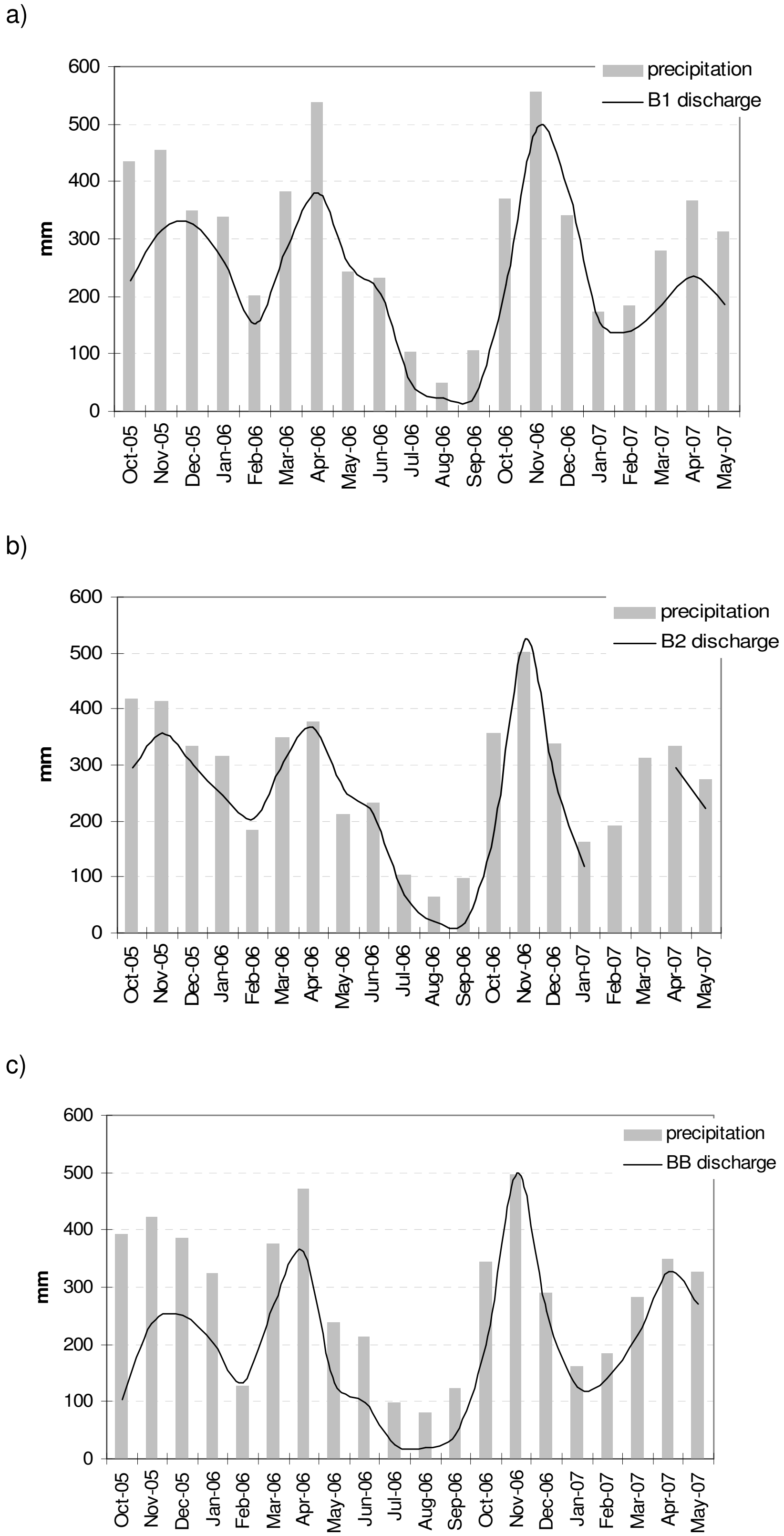


Figure 4-5 - Seasonal distribution of flow for; a) B1; b) B2; and c) BB.

4.4.6. Low flow analysis - flow duration curves (FDC)

Low flows are considered an integral component of the flow regime of any stream. Conceptually, a river catchment can be perceived as a series of interlinked reservoirs, each of which has components of recharge, storage and discharge. Recharge to the whole system is largely dependent on precipitation, whereas storage and discharge are complex functions of catchment physiographic characteristics. During a dry season the processes are significantly affected by catchment geology. Recharge, storage and discharge in the vicinity of the river channel are usually operative, as opposed to the full range of hydrological processes that operate over larger parts of the catchments during periods of higher discharge (Smakhtin, 2001).

Low flows can have several sources. In most cases the main source of stream discharge during low-flow periods is the release from groundwater storage, but can also be sustained by drainage of saturated top soil (Anderson and Burt, 1980). Gains to low flows can also be derived from the drainage of near surface valley bottom storages such as more permanently wetted channel bank soils, alluvial valley fills and wetland areas. These are areas where water becomes concentrated during and soon after precipitation events and therefore where adequate levels of storage are maintained during the dry season to ensure uninterrupted lateral drainage into channels (Smakhtin, 2001).

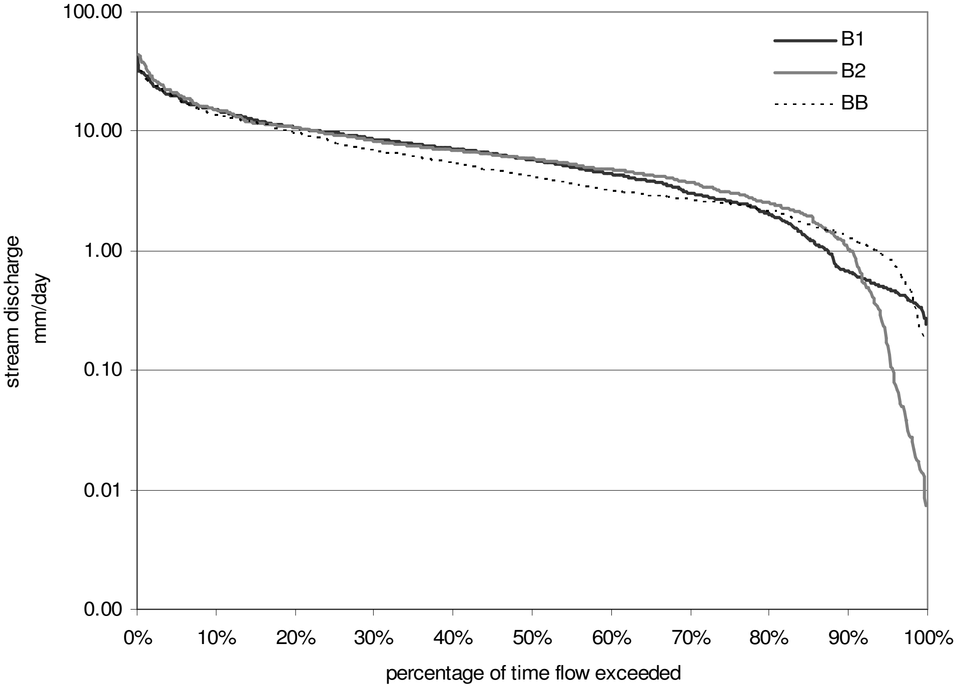
A flow duration curve (FDC) displays the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded (Smakhtin, 2001). For low flow analysis, the low flow section of a flow duration curve can be interpreted as an index of groundwater / sub-surface flow contribution to stream flow. If the slope of the low-flow part of the curve is small, the contribution of groundwater / sub-surface flow contribution is normally significant and low-flows are sustainable. A steep curve indicates small and/or variable base flow contribution (Smakhtin, 2001). The shape of a FDC is influenced by water resources development (water withdrawals, upstream reservoirs, etc.) and land use type (Smakhtin, 2001). The FDC for a catchment provides a graphical and statistical summary of the stream flow variability at a given location, with the shape being determined by rainfall pattern, catchment size and the physiographic characteristics of the catchment (Brown, et al., 2005).

The most widely used definition of low flow is any flow that is exceeded for 70-99% of the time (Smakhtin, 2001) and high or peak flows are considered the flows that are exceeded 1-5% of the time (Brown, et al., 2005). Figure 4-6a shows the FDC in mm per day for the 3 catchment streams and Figure 4-6b shows the same FDC in m^3/day which reflect the difference in catchment size. Considering the definition of low flows (flows exceeded between 70% and 99% of the time), only half the low flows present significant reductions.

B1 and B2 display similar behavior during 60% of the time when the flows are higher, although the large differences in event flows are not apparent on a log scale (Figure 4-6). When the flows are reduced in the dry season the flow of B1 decreases first. However, when the dry season advances, B2 shows a significant drop in flow. In the dry season B1 presents a significantly reduced flow, though an order of magnitude higher than the flow of B2. B2 has a discharge in the dry season opposite to what the annual water yield shows. This may be explained by the compaction of soil by grazing in the grasslands relative to the characteristics of soils in riparian or natural forests and the absence of the litter layer and canopy. Compaction reduces rainfall infiltration opportunities, making groundwater replenishment insufficient during the rainy season and producing strong declines in dry season flows (Bruijnzeel, 2004). This is contrary to the conclusions of the majority of studies conducted in temperate areas where as a result of deforestation increases of baseflow are almost consistently observed (Hornbeck et al., 1993, Andreassian, 2004).

BB has a smaller discharge in the medium range of flows in relation to the other two streams which explains why the annual water yield is smaller, but in the dry periods (10% of the time) its flow is higher than the other two streams. BB is the stream that sustains flow the longest in the dry season. It only drops below the B1 flow during the end of the dry season.

a)



b)

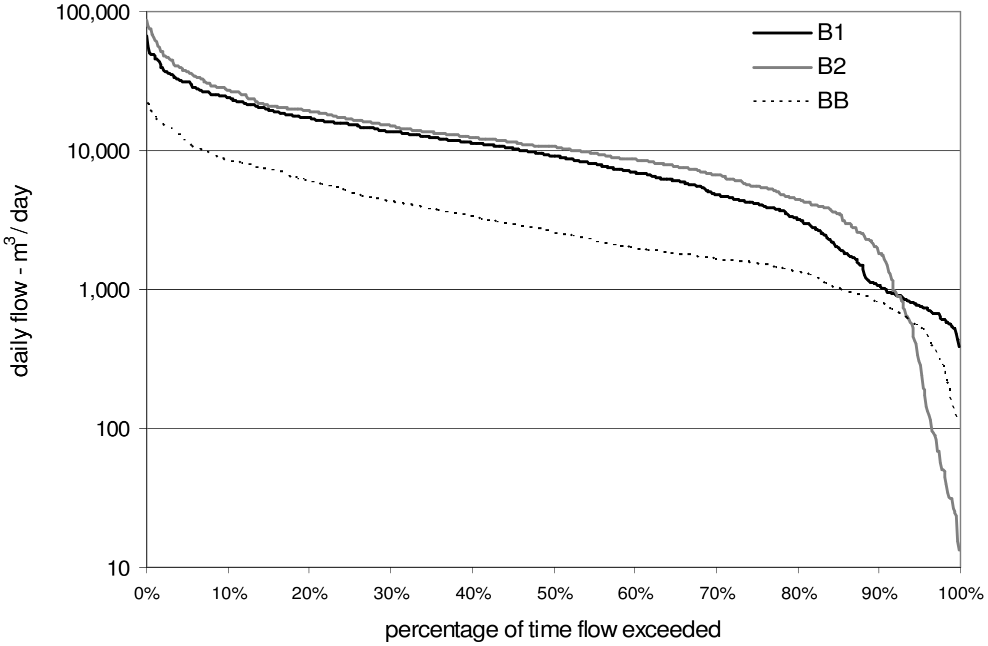


Figure 4-6 - Flow duration curves of daily stream discharge: a) flow in mm/day; b) flow in m^3/day

Comparative catchment studies involving wetlands are not very common. Burt (1995) compared three headwater catchments located in the Yorkshire region of Britain, one of them dominated by peat deposits. The three catchments compared had very different geology, precipitation patterns and soil types. The peat covered catchment located in the uplands, had an annual precipitation regime of more than double the other two catchments that were located in the lowlands. By comparison with the two lowland catchments, the peat dominated catchment generated large quantities of flood runoff since there was little storage capacity available, providing a flashy runoff regime (Burt, 1995). Assessments of the role of wetlands in headwater catchment hydrology require a closer observation of the paired catchment method in order to isolate the presence of wetlands from climatologic and geologic factors. In my study, a 6% wetland area in BB, a small catchment, could be a factor contributing to the maintenance of low flows, although a detailed analysis of topography would be required to quantify the differences in potential storage of water between the catchments.

Under mature tropical forest typically 80-95% of incident rainfall infiltrates into the soil (Bruijnzeel, 2004). The rate of evapotranspiration from undisturbed tropical forests is around 1400 ± 100 mm yr^{-1} (Roberts, et al., 2005) and close to 950 ± 50 mm yr^{-1} from grasslands in moderately seasonal conditions (Scott, et al., 2005 and Grip, et al., 2005). Based on these data, replacing forests with grasslands would be expected to produce an increase in annual water yield between 300-400 mm yr^{-1}, except if the forest cut was a cloud forest receiving an important amount of precipitation in the form of fog captured by the trees, or if the soils are degraded to the extent that more water is lost from the catchment during the rainy season than what is potentially gained by a reduced evapotranspiration (Bruijnzeel, et al., 2005).

Given the large precipitation and fairly high soil moisture content throughout the year, evapotranspiration in the three catchments is likely near the potential value. To differentiate potential ET from evaporation from an open surface, Penman (1967) used ratios of potential ET to open water evaporation and suggested using 0.7 as the ratio for a short grass in the humid tropics, and Pereira suggested 0.75 as the ratio for young pines in humid Kenya and 0.9 for mature evergreen rain forest in the same area (Pereira, 1967). This would suggest that in the dry season the forest demand for water could be estimated around 28% higher than that of grasslands. This difference is apparent in the evapotranspiration calculation for the catchments (Figure 4-7) and could help explain why the FDC for B1 shows lower flows per unit area than B2 for the flows exceeded between 60% and 90% of the time (Figure 4-6a).

Figure 4-7 - Average evapotranspiration for the three catchments for the period Oct 05-May 07.

One major difference between the two FDC comparisons of Figure 4-6 is that BB shows a higher discharge per unit area during the end of the dry season. The explanation may be in the presence of a large wetland with similar characteristics to the ones found in the smaller wetland located in catchment B2 described in Chapter 3. The main property of this wetland was its open surface water with no vegetation. There are only four wetlands with these characteristics in the entire study area and the largest one is located in BB catchment and has an area of 0.5 Ha. If this wetland has a similar behavior in the dry season to the one observed for wetland B2 and considering that it is almost 10 times bigger, it would help explain why catchment BB has a more sustained baseflow.

4.4.7. Storm flow analysis

Differences in the stream response to events were analyzed based on two indicators: the volume response to individual events (discharge coefficient) and the lag times in hydrological response from the peak in precipitation of individual events to the peak in stream discharge; as Table 4-8 shows, on average catchment B2 has a higher discharge coefficient (24%), which coincides with what was found in the seasonal yield analysis, where B2 had a higher water yield in relation to the other two catchments. BB shows the lowest average discharge coefficient (20%), but appears to have larger discharges values than the other two catchments for events Type 4 and 5 (large/intense and large and long events respectively) as can be seen in the boxplots of Figure 4-8. There appears to be no significant difference in discharge coefficients of the three catchments for event Types 1, 2 or 3 as illustrated in Figure 4-8. B1 is the catchment with the lowest discharges for all event types and seasons. Catchment B2 shows significantly higher flows for all types of events and the highest maximum values of discharge. This makes apparent the influence of forests on reducing discharge during rain events (B1); and the possible "bursting" effect of wetlands during intense and/or large events that could increase the discharge of their host catchment (BB). Average values of discharge for each catchment by event type and season are included in Appendix 9.

The comparative results for B1 and B2 are consistent with what has been found in temperate areas where paired-watershed comparisons have shown that deforestation often increase both flood volumes and flood peaks. However, this effect is much more variable than the effect on total flow and may even be reversed in some years or in some seasons (Andreassian, 2004). The discharge values for large/intense events of catchment BB are compatible with other wetland studies that have found wetlands as factors of increased flood peaks (Bullock and Acreman, 2003).

Table 4-8 - Stream event discharge

season	N	median precip. (mm)	discharge coefficient
B1			
Dry	112	10.1	11%
Wet	315	12.7	26%
Average			22%
B2			
Dry	91	10.0	13%
Wet	318	11.4	27%
Average			24%
BB			
Dry	110	10.3	9%
Wet	325	11.9	24%
Average			20%

The annual precipitation in the region is concentrated in large events of high intensity; 34% of annual precipitation corresponds to events Type 4, as seen in Appendix 3. Although wetlands do not retain as much water as forests during these types of event, they still appear to reduce the annual water yield of the catchment (Figure 4-3).

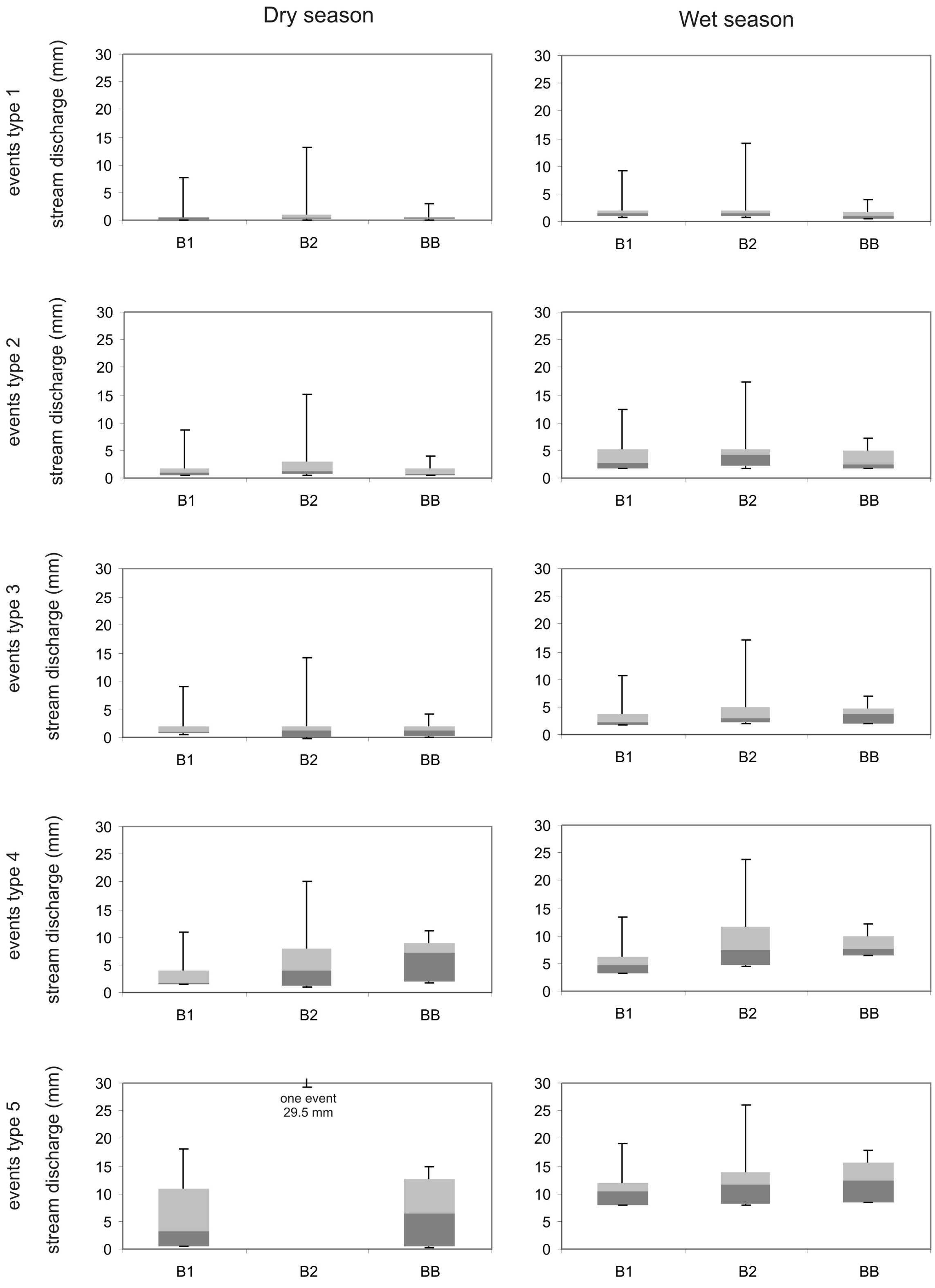


Figure 4-8 - Discharge coefficient for catchments by season and event type. Median, lower and upper quartiles, and min and max observations.

The lags from peak precipitation to peak discharge for the three catchments show that other factors besides catchment size are influencing the lag times to peak in discharge (Table 4-9). Despite BB being almost a third of the size of B1 and B2, the lag times to peak in the wet season are very similar. McGlynn et al. (2004) showed that for catchments bigger than 17 ha, size produces an effect in hydraulic lag. In this case the difference in time lag to peak between the three catchments is small, all lags being around 1.8 hours and shorter for intense events (types 3 and 4) for all streams in the wet season (shown in Appendix 7).

Table 4-9 - Time lag to peak in flow for streams and wetlands

	B1		B2		BB	
streams						
area (ha)		158.6		179.1		61.9
Season	N	tlpf (min)	N	tlpf (min)	N	tlpf (min)
Wet	309	109	303	112	321	117
Dry	109	132	90	134	106	104
wetlands						
area (ha)		0.9		2.5		8.9
Season	N	tlpf (min)	N	tlpf (min)	N	tlpf (min)
Wet	88	46	312	52	299	118
Dry	43	53	82	44	99	90

The hydrographs of the three catchments and corresponding wetlands show that the differences in discharge volumes and lag times depend on the type of rain event. To analyze the capacity of wetlands and catchments to attenuate rain events, typical events Type 3, and 4 in the wet season are shown in Figures 4-9 and 4-10.

Event Type 3 shown in Figure 4-9, which is a medium size event (with total precipitation between 10 and 20 mm) of high intensity in the wet season produces a larger discharge in B2 catchment compared to the other two catchments; and BB wetland shows a smaller response compared to the other two wetlands. Events type 4 (Figure 4-10) which are the large intense events, produce a large discharge in B2 catchment compared with the other 2 catchments (similar to event Type 3); but the discharge from wetlands are an order of magnitude larger than for an event type 3. For B1 wetland, this might not be very significant since this wetland has a very limited capacity to store water, but for BB, this implies that large intense events can produce a “burst” of the wetland. This is also evident in the lag times. For event Type 3 (Figure 4-9), wetland BB presents a delay in response to precipitation, being almost synchronized with the catchment. For the event Type 4 (Figure 4-10), BB wetland presents an earlier peak, implying a negative effect for rain event attenuation. Example hydrographs of the response to an event type 4 occurring in the dry season and for an event type 5 in the wet season are included in Appendix 10.

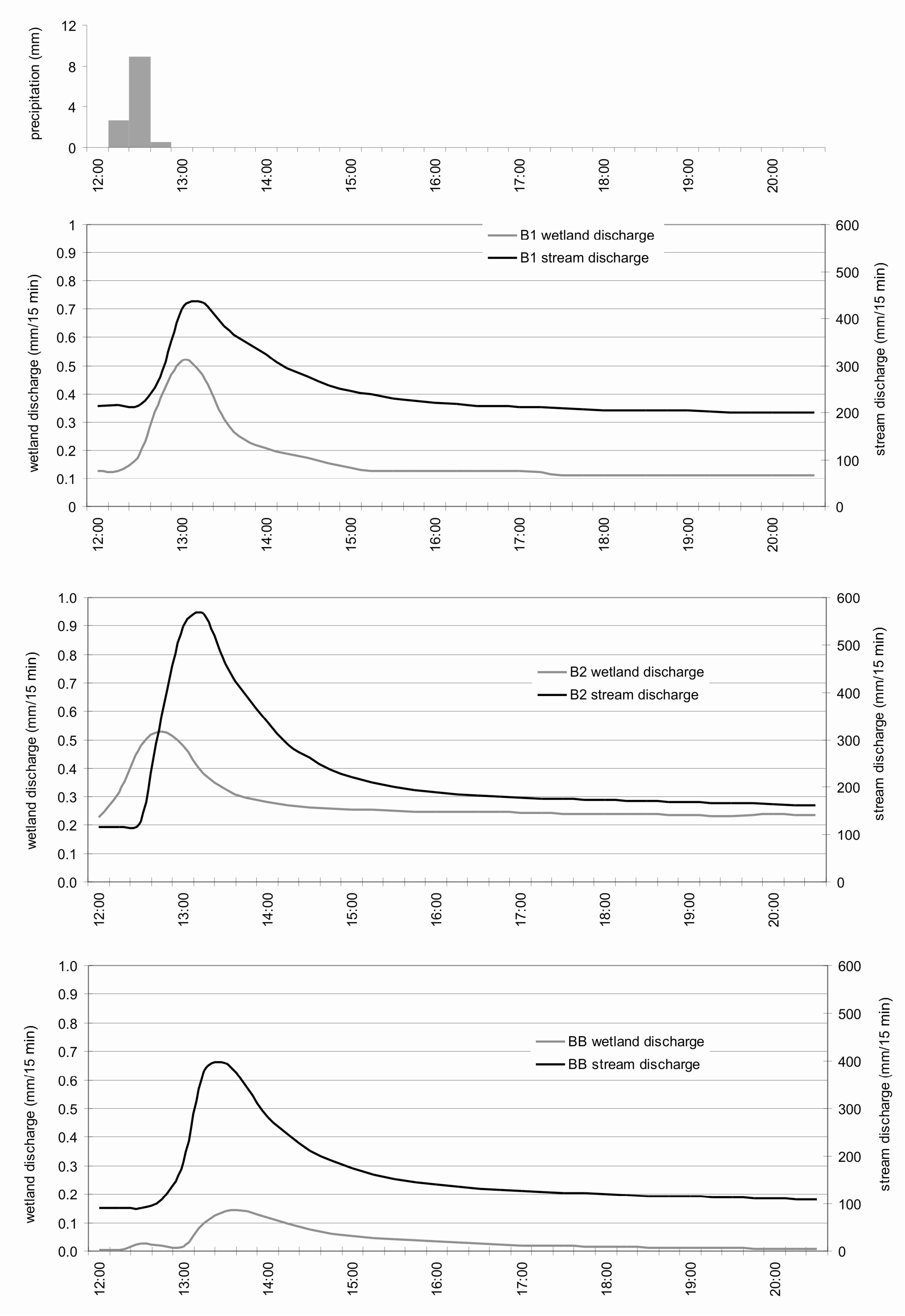


Figure 4-9 - Streams and wetlands hydrograph for event type 3 (Sep. 9th, 2006)

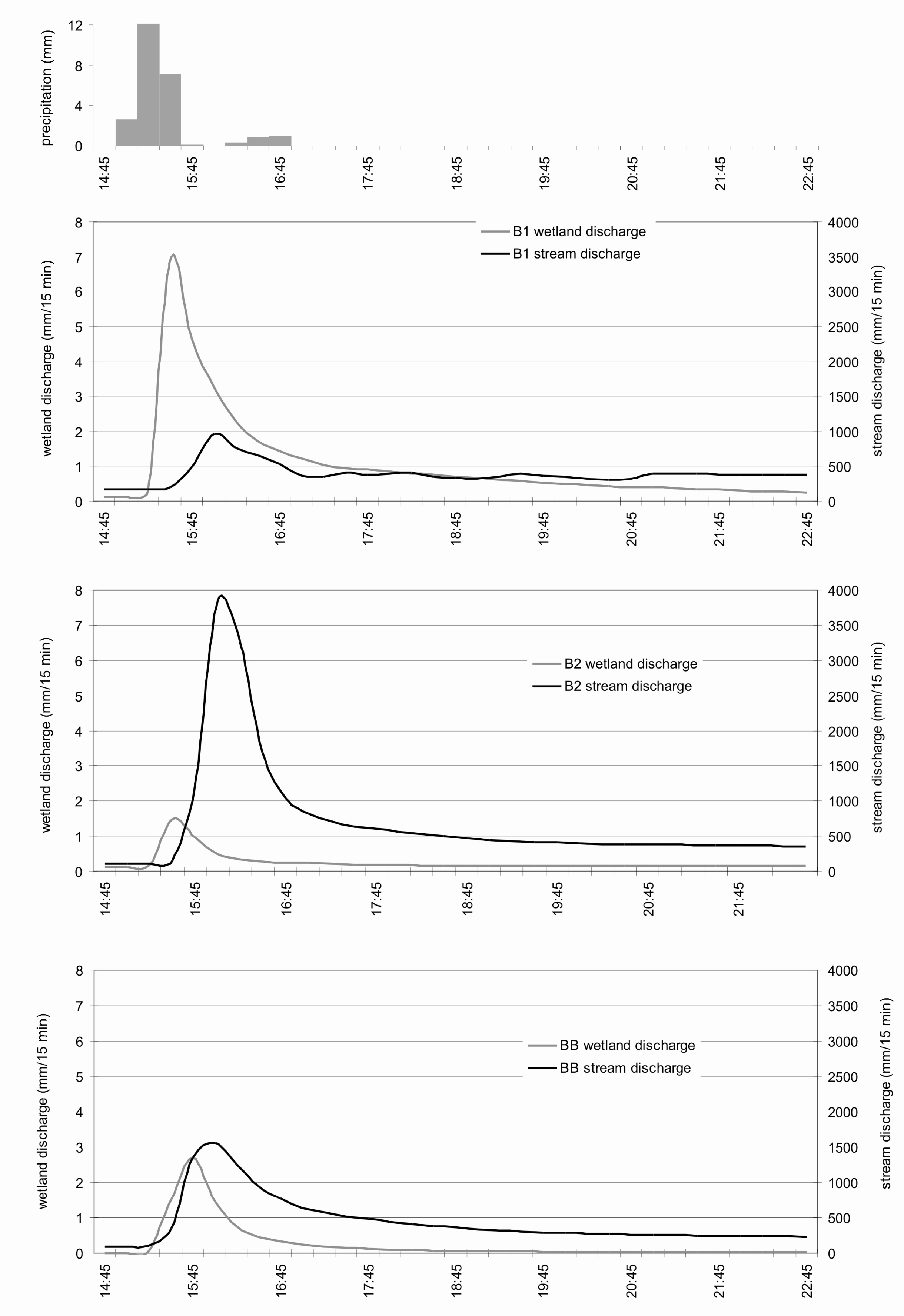


Figure 4-10 - Streams and wetlands hydrograph for event type 4 (Nov. 11th, 2006)

The linear reservoir concept is used to assess the overall retention capacity of the catchments in terms of peak flow. In this model, based on the recession limbs of the drainage hydrographs, every catchment is considered as a series of independent reservoirs, each characterized by mean residence times (T). T is related to the time required for water to travel to the catchment outlet, and so it is dependent on watershed size (larger catchments have larger T), soils and geology, slope and land use (Dingman, 1994).

The linear reservoir concept is a tool to compare the behavior of catchments by splitting events into three reservoirs of discharge, each of them with a particular time of discharge – T. The three reservoirs represent pools of water that flow into the stream in a short, medium and long period of time. The comparison of these times provides an idea of the regulatory capacity of the catchments' soils to hold and discharge water.

Out of the 15 events considered for this analysis, 11 were events of more than 20 mm in total, duration of 5 hours or less and exhibited even spatial distribution (large intense events). Two of the analyzed events had a total precipitation between 10 and 20 mm with maximum 30 minute intensity of 10 mm or less and an even spatial distribution (medium intense events); one event had a total precipitation between 10 and 20 mm with maximum 30 minute intensity of more than 10 mm and an even spatial distribution (medium and slow event); and one event was a large intense event in two catchments and a medium slow event in the third catchment. In consequence the analysis has been done predominantly for large intense events, as shown in Table 4-10.

Table 4-10 - Summary of events used for linear reservoir calculation

Event type			Average precipitation (mm)
B1	**B2**	**BB**	
1	1	1	6.9
4	4	4	29.3
3	4	3	29.8
1	1	1	8.8
4	1	4	29.3
4	4	4	29.2
4	4	4	21.3
3	3	3	18.4
4	4	4	24.1
4	4	4	25.7
4	4	4	26.4
5	5	2	20.8
4	3	4	27.1
4	2	4	19.9
4	4	4	36.8

The median time for each of the three theoretical reservoirs to drain out of the catchments is shown in Table 4-11.

Table 4-11 - Median indices of water release, T

	B1	Stand. Dev.	B2	Stand. Dev.	BB	Stand. Dev.
T1 (h)	9.1	± 6.2	8.0	± 5.4	7.4	± 5.5
T2 (h)	25.9	± 26.4	25.8	± 16.4	16.6	± 15.0
T3 (h)	137.4	± 66.9	116.9	± 65.6	57.1	± 30.3
Area (ha)	158.6		179.1		61.9	

The higher the values for T, the longer it takes for the water to leave the catchment. These results indicate that although B2 is a larger catchment than B1, T1 and T3 are smaller than for B1 showing the impact of the predominance of grasslands in B2, whose soils have a reduced porosity in comparison with natural forest. It is also evident that BB with almost a third of the size of B2, has values for T that indicate a larger water storage capacity per unit area, which can be attributed to the wetlands, given that slope, soils and geology are similar. B2 has a faster speed of drainage considering its size, which helps to explain the characteristics of its flow duration curves during the dry season.

A similar study conducted in the Andes of Ecuador comparing two high elevation headwater catchments (at around 4,000 meters) showed values for a cultivated (impacted) catchment for T1 of 3.6 hours, for T2 of 27.2 hours and for T3 of 175 hours; and for an undisturbed catchment values for T1 of 5.4 hours, for T2 of 44.3 hours and for T3 of 360 hours (catchment size 190 and 230 ha respectively). The study shows a difference of about 40% in the rate of water release between the two catchments (Buytaert, et al. 2004). In the present study, T1 values for the three catchments are slower but for T2 and T3 they are faster and closer to the values presented for the cultivated (disturbed) catchment of Buytaert. It is likely that the combination of clayey, shallow young Andisols, and a predominant land use of cattle grazing, reduces the capacity of soils to store water and makes water release from these catchments similar to the one found from highly impacted catchments in Ecuador.

4.5. Conclusions

Different methods have been used as part of a comparative catchment approach to assess the effect of wetlands and land use in headwater catchments on stream discharge. The comparative catchment approach minimizes variability related to climate, geologically determined differences in groundwater reserves and deep percolation; spatial and year to year variability.

Due to previous studies of the area, wetlands were initially hypothesized as being the main factor causing differences in stream discharge. They were previously estimated to cover 43% of BB and 11% of B1 and B2 together. From this research differences in forest cover between the catchments were found to be more important than wetlands and the latter appear to play a major role influencing discharge.

The analysis of soils moisture curves has shown that the soils have low infiltration, large storage capacity but slow water release. As a result the water yield of catchments at different time scales (monthly, seasonally and annually) showed the effect of the reduced infiltration capacity of soils when converted to grasslands.

The FDCs illustrated the significant effect of land use on stream discharge, by highlighting the differences in the low flows period for the three streams. The base flow for B1 is the highest at the end of the dry season, despite having a high percentage of area in natural and riparian forest. The FDCs also show that per unit area, catchment BB has a slower reduction in flow than the other two catchments. The explanation for this was found in the existence of a 0.5 ha wetland with similar characteristics to a monitored wetland with a water yield in the dry season that is relatively higher than the water yield of its host catchment.

The analysis of discharge coefficients has shown that forests, given their significant coverage of area in the catchments, appear to have a large influence in regulating stream event discharge illustrated by the large discharge response of B2 catchment (the one with less forest coverage) to medium and large size events in comparison with B1 (the one predominantly covered by forest).

Lumped lag times do not show significant differences between the peak in rain event and the peak in discharge for the dominantly forested catchment (B1) and the dominantly grassland covered catchment (B2); and they contrast with the linear reservoir analysis that showed a slower release of water for catchment B1. What this indicated is that both catchments have a synchronized peak but the rate of water release is different, the forested catchment having a slower release of water.

Lag time differences coincide with the linear reservoir analysis for the comparison between BB (the catchment with a 6% of area in wetlands) and B2. They indicate that despite the smaller size of catchment BB, there is a delay effect of peaks and water release, which could be attributed to the presence of wetlands. BB is also the catchment with the smallest average discharge coefficient, although discharge for intense and/or large event is larger than for the other two catchments. A detailed topographic study would be necessary to separate the effect of topography from the existence of wetlands in 6% of the area of catchment BB since this percentage of area in wetlands is considered small to produce such large differences in discharge coefficient, lag times and annual yields.

Wetlands show a variety of behaviors depending on their water holding capacity (given by size, topography and physical characteristics) and the type (amount, intensity and duration) of rain event. The largest wetland appears to have a dampening effect of small to medium size events, but it appears to have a “burst” and rapid response to large events.

The use of the linear reservoir concept corroborates the results of the FDCs by showing that despite the larger size of B2, the time the water takes to leave the catchment is shorter than for the other two catchments. This indicates a smaller water storage capacity, related to grasslands that have less capacity to store water than forests.

The dynamics of Andisols in relation to water storage and release is characterized by a large capacity to hold water, and a poor potential for releasing it. What this means is that these soils are likely to remain moist and do not facilitate the movement of water in the soil matrix. It also reduces infiltration rates and increases the chances of surface runoff. This was illustrated by the soil moisture curves and supported by the small soil moisture fluctuations throughout the year, the low K_{sat} - saturated hydraulic conductivity rates and high proportions of surface runoff for days of heavy rain. This characteristic of the soils in the studied catchments amplified differences in land use, and exemplified the importance of soils in the hydrological dynamics of catchments.

Wetlands were found to occupy a small percentage of the total area of the three catchments studied, less than they were previously thought. They were found to be concentrated in one of the studied catchments (BB) where they reach a 6% of the total area. This area of wetlands is the only major difference found in the land use between catchments B2 and BB and based on this difference the effects of wetlands in catchment hydrology could be identified. Wetlands appear to delay the reduction of catchment flows in the dry season, as was illustrated through the FDC. However, based on the distinctions made in the previous chapter, not all the wetlands contribute to this effect. Only wetlands with a surface outflow and a portion of their total area as an open water surface were found to make a contribution to dry season flows. A large wetland of 0.5 ha with such properties was found in catchment BB, which explains why this catchment has a higher flow per unit area during a large portion of the dry season.

A large difference in area of forest was found between catchment B1 and the other two catchments and based on this difference the effects of forests on catchment hydrology were identified. FDC showed that catchment B1 has a faster decrease in flow per unit area when the dry season starts, which can be attributed to a higher rate of evapotranspiration from trees in comparison with grass. But as the dry season advances, soils under forests appear to sustain flows at a higher rate than soils under grasslands. This supports the “infiltration trade-off hypothesis” for tropical environments.

Forests also demonstrated to produce a significant effect in dampening discharge of rain events in water volume released during and immediately after the rain event. There is no significant difference in lag time from the peak of the precipitation to the peak in discharge between catchments B1 and B2. This means that the forests do not produce a delay in the peak discharge. Considering the smaller size of catchment BB, its lag time to peak in discharge is larger, suggesting the influence of wetlands in delaying peak discharge.

Less clear, is the contribution of wetlands to smaller discharge coefficients. The three catchments show very similar discharge coefficients for small events, but BB shows a higher discharge for large events. The delayed peak and the large discharge coefficient suggest that wetlands could "burst" as a consequence of saturated conditions after large events.

The linear reservoir concept allowed the comparison of the residence time of water during an event. The results indicate that water required more time to leave the forested cacthment, but that wetlands have a significant effect in prolonging the residence time. Even though catchment BB had higher discharge coefficients for large events, the linear reservoir concept showed that on a per unit area basis, water took more time to leave BB in relation to the other catchments.

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5. Transit times and hydrograph separation in headwater catchments of the Andes[1]

5.1. Introduction

Effective water management whose aim is to sustain catchment ecological services requires an understanding of the hydrologic cycle, including the size and characteristics of the ecological components that comprise the catchment and the dynamics of flow among those components. The application of isotope methods has advanced the understanding of water flow dynamics. Water isotopes have been used in hydrology for two purposes: 1) to identify the transit time of water when it leaves a catchment, both for baseflow and for individual storms; and 2) to identify the temporal source of water that leaves the catchment during a runoff event, (e.g. whether it comes from rain or snowmelt (event water) or from water stored in the watershed prior to the event (groundwater, soilwater, lakes etc.). This knowledge has been used to understand the interactions between precipitation, runoff pathways and runoff generation processes, and as a proxy for the capacity of a catchment to store water and regulate its flow.

Comparative studies to differentiate between the effects of alternative land use types on residence time of water can provide information to environmental managers about effective ways to preserve desirable hydrological functions of headwater catchments. This information can support decisions on which components of the catchment landscape are more effective in retaining stormflows and maintaining baseflows.

This study aims at complementing the hydrologic analysis that has been done for three small headwater catchments in the mountains of Colombia, that constitute the water source for a municipality of 15,000 people and their economic activities. The isotopic analysis of hydrological processes in these catchments will contribute to elucidate the influence of the catchment components on the hydrological response of the catchments. The three small neighboring headwater catchments and one sub-catchment in each, which contains a wetland were compared. The dominant land uses are grasslands and forests but significant differences between the catchments have been quantified. The objective is to quantify and compare the transit time of water in each of these units at two flow conditions: events and baseflow. This will show the effect of land use on these two types of flow conditions. The study will apply models previously developed for the estimation of transit time of water in catchments and hydrograph separation, to data collected in the study area and will focus on the interpretation of results for the effects of land use on hydrology.

There are two underlying principles behind the use of isotopes in catchment hydrology. Firstly, the tracer composition of precipitation that falls on a catchment will be delayed by some timescale(s) before reaching the stream (McGuire et al., 2005). Therefore the stream outflow composition at anytime

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will consist of past inputs lagged according to their residence time distribution (Maloszewsky and Zuber, 1982). This logic is used to derive the transit time model, which represents the tracer transfer function. The travel time or transit time distribution describes the fractional weighting of how the water mass exists the system, which is equivalent to the transfer function of isotopes applied to the catchment (McGuire et al., 2005).

The second principle in isotope use for hydrology is that the combination of the tracer transport time concept and the hydraulic transfer function is essential to understand catchment behavior, since the first one represents the actual tracer travel time (along flow paths) and the second represents hydraulic dynamics (e.g. rainfall-runoff behavior) (Weiler et al., 2003). These two processes have different time scales because the fluctuations in hydraulic head (the driving force in water flux) can propagate much faster than the transport of individual water molecules (McGuire et al., 2005). What this approach does is to combine and integrate the isotope hydrograph separation – IHS, which has been used for the past two decades, and the instantaneous unit hydrograph – IUH, for better quantification of event and pre-event water contribution to storm runoff. This approach is used to estimate event water transit time distributions for discrete events combining the benefits of tracer-based hydrograph separation with the hydraulic transfer function approach (Weiler et al., 2003).

The isotopic hydrograph separation model provides information on such characteristics as event water (percentage of the discharge that comes from precipitation) and pre-event water (Weiler et al, 2003); the transit time model provides information about the mean transit time of water in the catchment (MTT) under baseflow conditions (McGuire and McDonnell, 2006), and under runoff events. Hydrograph separation has been considered secondary when the goal is to predict streamflow, but considered useful to predict water quality (Bariac et al., 1995).

Among the main contributions of this method for small catchments in temperate areas is that there is a large range in pre-event water fractions of stormflow (Buttle and McDonnell, 2005) depending on several factors such as topography, catchment size, land use, degree of soil compaction, precipitation event types (Shanley et al., 2002) and antecedent wetness. In general the land uses or surface types that promote surface runoff produce smaller fractions of pre-event water. In temperate areas the surfaces with these characteristics include urban, permafrost or forests with frozen soils (Buttle and McDonnell, 2005).

Comparative studies conducted to identify the effects of disturbance or land use change on the hydrograph separation have been few (Buttle and McDonnell, 2005). In temperate environments, Gremillion et al. (2000) quantified the reduction in pre-event water with the increased urbanization of a catchment in Florida; Laudon et al. (2007) working in boreal catchments, determined that pre-event water in wetland dominated catchments were around 50% while in forested catchments it was between 10% and 30%. In tropical environments, isotopic hydrograph separation has been limited. A study by Goller et all. (2005) in the Ecuadorian Andes found event water dominated discharge; and in Zimbabwe McCartney et al. (1998) found that for a catchment with a large proportion of its area covered with a wetland, the proportion of pre-event water depends on the size of the event.

Results suggest that origin and flow paths of water are the main factors determining mean transit time, more than catchment size. There are other first-order controls such as the hydrological response of definable landscape units (McGlynn et al., 2004). In fact, studies by McGlynn and Seibert (2003) have determined that runoff is predominantly generated in sub-80-ha riparian zones and transferred downstream through the channel network to the catchment outlet.

The similar runoff coefficients (percentage of volume of water flowing to the catchment outflow compared with the event precipitation) found for catchments at the Maimai region in New Zealand with sizes between 2.6 and 280 ha, show that there is no clear relationship between catchment size and yield (McGlynn and McDonnell, 2003).

In tropical environments, Bariac et al. (1998) comparing two catchments of 1.3 and 1.6 ha in French Guiana, found that the deforested catchment had a runoff coefficient (percentage of volume of water flowing to the catchment outflow compared with the event precipitation) of 41% while the forested catchment had a runoff coefficient of 28% probably due to the combined effect of interception and the action of the vegetation on soil porosity.

5.2. Study site

Three adjacent small headwater catchments draining to the same river system were selected for a comparative study of land use and stream flow to quantify the impact that different land use types have on stream flow. These catchments are located in the coffee growing region of Colombia (Figure 5-1), on the western side of the central branch of the Andes and drain to the Cauca River, which flows north to the Atlantic Ocean. Most of the land in the three micro-catchments is dedicated to extensive cattle rearing but differences in land use can be seen among the three catchments. The parent materials of the soil are fluvio-volcanic sediments (mostly clays of uniform size and arranged with pockets of crystalline coarse fragments). The geological unit has a volcanic ash layer which can reach up to tens of meters in thickness at some locations, is characterized by very low hydraulic conductivity, which contributes to the formation of wetlands, limits water percolation and contributes to maintaining a high water table. Soils formed on these sediments are classified as Andisols (Acrudoxic Hapludans) (IGAC, 1996) characterized by high organic matter content and high content of allophanes and imogolite, which combined produce soils of high water holding capacity.

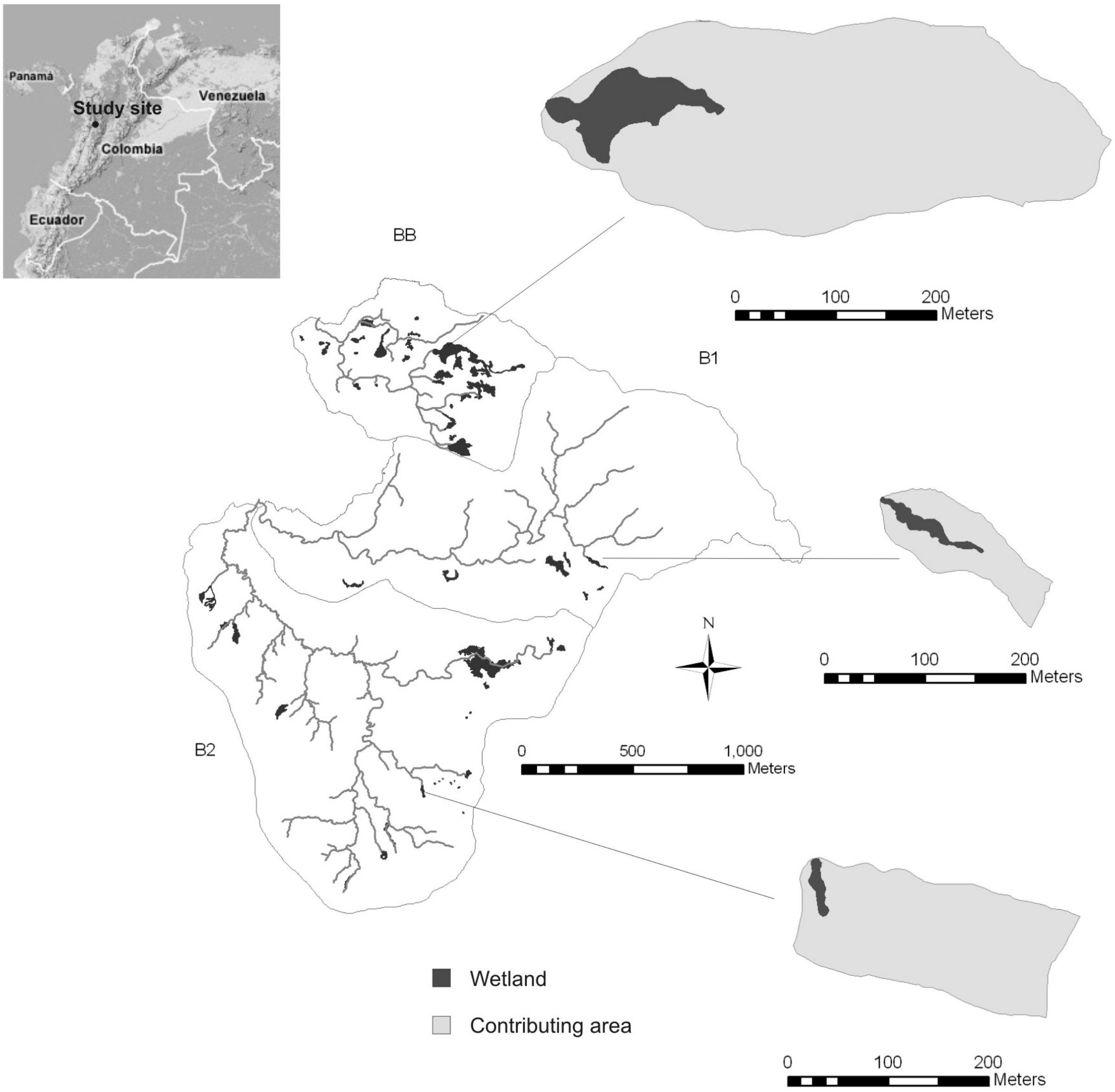

Figure 5-1 - Location of study site, and monitored catchments and wetlands

The wetlands chosen for monitoring (B1W, B2W and BBW) are permanent wetlands with surface outflow and rain as their only water source. Table 5-1 summarizes the characteristics of the monitored wetlands and their contributing areas (chapter 3).

The stream catchments (B1S, B2S and BBS) differ in size and land use (Table 5-2). BB is the smallest catchment, but has the largest proportion of wetlands. B2 is the largest catchment with the highest proportion of grasslands. And B1 is smaller than B2 but has a larger proportion of natural and riparian forest.

Table 5-1 - Characteristics of wetland catchments

Wetland	Fence	Maximum depth (m)	Average organic matter content (%)	Soil porosity of organic layer (%)	Wetland area (m^2)	Contributing area (m^2)	Wetland area: Contributing area ratio
B1	No	2.1	20	79	1,072	9,854	1:9
B2	Yes	2.8	38	91	553	25,600	1:46
BB	Yes	2.4	33	86	6,650	89,051	1:13

Table 5-2 - Land use areas per stream catchment

	B1		B2		BB	
	ha	%	ha	%	ha	%
Riparian and natural forest	81.2	51	48.9	27	15.6	25
Plantation forest	27.7	17	1.9	1	3.3	5
Grasslands	47.7	30	123.6	69	38.7	62
Wetlands	0.8	1	2.7	1	3.8	6
Roads and buildings	1.2	1	2.1	1	0.6	1
Total area	158.6	100	179.1	100	61.9	100

Figure 5-2 shows the concentration of natural and riparian forests in B1, and of grasslands in B2 and BB. It is also evident that wetlands occupy a larger percentage of the catchment area in BB.

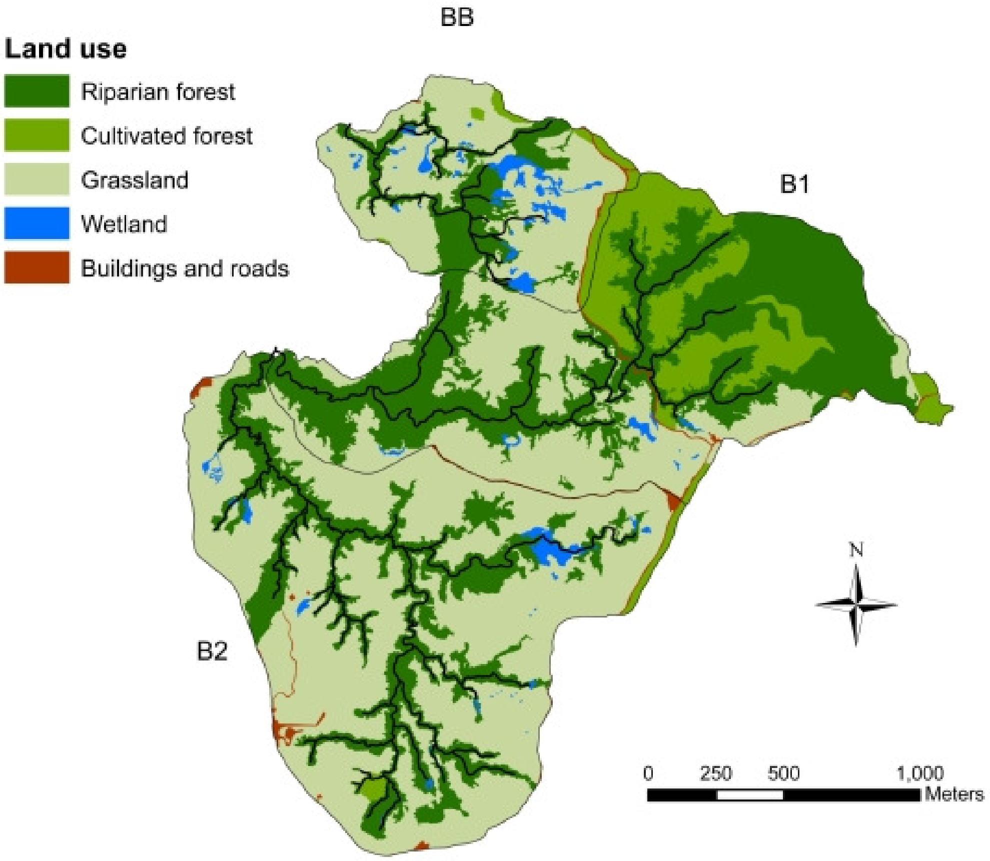

Figure 5-2 - Land use map for the 3 micro-catchments

5.3. Methods

5.3.1. Hydrological monitoring

Streamflow was monitored at the outlet of the three catchments and at the outlet of one wetland within each catchment as shown in Figure 5-1. This was done with three AquiStar PT2X Smart Sensors© to monitor water levels at the catchment outflows and three Odyssey© capacitive water level recorders for the wetland outflows. Water level was recorded every 15 minutes from June 2005 until May 2007. These water level data series were converted into flow measurements with stage-discharge relations by 62, 44 and 50 discharge measurements for catchments B1, B2 and BB respectively using a current meter from OTT© – Messtechnik GmbH & Co. For wetlands, flow measurements were taken using the salt dilution method for the wetlands with 15, 22 and 14 discharge measurements for wetlands B1, B2 and BB respectively. Precipitation was measured in each of the catchments using three Hobo Pro© data logging rain gauges located in the contributing areas of the three wetlands.

5.3.2. Rain and runoff sampling for isotope analysis

5.3.2.1. For baseflow analysis

Rain samples were taken every two weeks from November 2005 until May 2007 (n = 39). Rain was collected according to guidelines from the isotope hydrology laboratory of the International Atomic Energy Agency – IAEA (IAEA, 2002). The water accumulated every two weeks was mixed in the container and a sample was taken at the end of the sampling period. At all six gauging stations, stream water samples were manually taken every two weeks, from May 2006 to May 2007 (n = 332). Samples were also taken from a drain gauge located at a depth of 2 meters (n = 30), and from a forested sub-catchment of catchment B1 (n = 17).

5.3.2.2. For storm analysis

Seven storm events were sampled during two rainy seasons in 2006 and 2007, of which five events were selected for modeling due to their completeness: November 14th of 2006 (event 2), November 21st of 2006 (event 3), April 7th 2007 (event 5), April 18th 2007 (event 6) and April 25th of 2007 (event 7). The rain samples were taken manually and a group of six people participated in the collection of samples for each event. The sequence of rain samples was determined by the speed at which vials could be filled with rain. From the three streams and three wetland outflows, a baseflow sample was taken before the rain started. Once the water level started rising, samples were taken every 20 minutes until the peak was reached when another sample was taken. After the peak, four samples were taken every 30 minutes and then every two hours until the water level returned to baseflow. For the collection of baseflow samples, one or two people collected samples every morning during the rainy period from each of the six catchments, since storm events were expected in the first few hours of the afternoon (Appendix 3, Figure 1b). If chances of a storm were relatively high one person was stationed in each catchment outflow (three catchments and three wetlands) from the beginning of the storm until the last sample of the 30 minutes intervals was taken; after that, a group of three people would move between the sites to collect the samples every two hours. The number of samples was 104 for event 2, 83 for event 3, 71 for event 5, 95 for event 6, and 86 for event 7. Precipitation and discharge samples were taken in high density polyethylene scintillation vials with cone caps.

The oxygen isotopic composition of samples was determined at the mass spectroscopy laboratory of the University of Idaho. The oxygen 18 composition ($\delta\ ^{18}O$) values are reported in per mil (‰) relative to a standard as $\delta\ ^{18}O = (R_x / R_s - 1) \times 1000$, where R_x and R_s are the ^{18}O / ^{16}O ratios for the sample and standard (VSMOW), respectively. Analytical error was ± 0.08%.

5.3.3. Assumptions for isotopic analysis in isotopic hydrograph separation

To obtain reliable hydrologic information from isotopic analysis, five assumptions are needed (Buttle, 1998). The first one is that there is a significant difference between the isotopic content of event and pre-event components; this assumption has been verified and is valid for the present study. The second one is that isotope signature of event water is constant in space and time, or any variations can be accounted for; given that the catchments are small and adjacent, it is assumed that the isotope signature of event water is constant spatially; it is known that the isotope signature of rain is not constant in time (Kendall & McDonnell, 1993), for this reason efforts have been made to incorporate this variability into the hydrograph separation procedure. One of these efforts is the transfer function hydrograph separation model (TRANSEP) designed by Weiler et al. (2003), which is used in this study. The third assumption is that the isotope signature of pre-event water is constant in space and time, or any variations can be accounted for; this assumption is not always verified (Bariac et al., 1995) and for this study it is assumed as valid. The fourth assumption is that contributions of water from the vadose zone to stormflow must be negligible, or the isotopic content of soil water must be similar to that of groundwater; this assumption is generally justified since baseflow coming from groundwater does not generally offer geochemical discontinuity (Bariac et al., 1995). Finally, it is assumed that contributions to streamflow from surface storage are negligible; this assumption is rejected since wetlands are considered surface storage and are one of the main foci of this study. One of the objectives of the analysis will be to estimate the contribution that wetlands are making both to baseflow and event discharge. On the other hand, given that this is a comparative study of adjacent catchments with differences concentrated on the proportions of land use types, assumptions three, four and five are less relevant since the results will be relative among the units of comparison.

5.3.4. Models used for event and baseflow analysis

5.3.4.1. Transfer function and hydrograph separation model for event analysis – TRANSEP

TRANSEP is a quantitative approach to describe the residence time of solute transport and transmittance of hydraulic behavior to help understand the relationship between pre-event and event water delivery to streams (Weiler et al., 2003). It uses water flux and isotopic data from precipitation and streamflow to derive transfer functions of runoff, event and pre-event water by capitalizing on the temporal variation of rainfall tracer composition. The mean residence time of water in the catchment is derived from adjusting the transfer function to optimize the fit between measured and computed stream water isotope content (Vitvar et al., 2005). The transfer function has been chosen from distribution models previously designed including the exponential, the exponential piston-flow and dispersion distribution (Maloszewski and Zuber, 1982), the gamma distribution model (Kirchner, et al., 2001), or the two parallel linear reservoirs model (Weiler et al., 2003).

The input data for this model corresponds to precipitation amount in 15 minute intervals and the corresponding isotope composition for precipitation in those time intervals for the duration of the precipitation event sampled; and discharge data every 15 minutes for approximately 24 hours and the corresponding isotope composition data interpolated for the same time intervals. The output hydrograph data is consequently given in the same 15 minute time intervals.

Weiler et al. (2003) tested these models for the Maimai catchments in New Zealand and obtained best results from the two linear parallel reservoirs. This is the model used for the present study. TRANSEP is used to detect differences in runoff and pre-event water transfer due to land use changes. It was run for each of the events sampled to determine the proportions of event and pre-event water for each of the six catchments.

5.3.4.2. Transit time model for baseflow analysis

The convolution model used to estimate mean transit time of water was based on the work by McGuire et al. (2005) using the two parallel linear reservoirs distribution. This model was selected due to its performance and fit to the study data. The model describes the probability density function of the tracer applied to the catchment and assumes that the Transit Time Distribution – TTD of the tracer is equal to the transit time of water in the catchment.

Mean Transit Time (MTT) is defined as the average time elapsed since water drops entered the catchment and the time they are observed in the catchment outlet (Vitvar et al., 2005). Mean Residence Time is the time that has passed once water molecules entered the catchment at any point along the flow path in the catchment (Maloszewsky and Zuber, 1982). Mean Transit Time and Mean Residence Time are indicators of transport time of individual tracers or water molecules. Both are indicators of the catchment response to water withdrawals, contamination or land use changes, and provide a basis for assessing sensitivity to imposed catchment management practices (Alley et al., 1999). They indicate the catchment's memory to past inputs and can thus be used as proxies to understand the hydrologic sensitivity to land use and climate change (McGuire et al., 2005). Given the similarity between these two terms, this paper will only deal with MTT.

Mean Response Time (MRT) on the other hand, is an indicator of the rainfall-runoff response; therefore it is an indicator of the speed of water in the catchment. MTT and MRT are indicators of decoupled processes that occur at different time scales. Since the fluctuations in hydraulic head (the driving force in water flux) can propagate much faster than individual water molecules, the MRT is expected to be shorter than the MTT.

For the baseflow analysis, MTT is estimated using bi-weekly discharge isotope composition records for 12 months (May 2006 to May 2007), bi-weekly precipitation isotope composition records for 19 months (November 2005 to May 2007), and precipitation records of 29 months (Jan 2005 to May 2007). When the MTT in a catchment is sufficiently longer than the input record, parameters such as MTT will be poorly estimated. With a transit of around one year, only a record of five years or longer would allow all the inputs to pass through the catchment and produce a good estimate of these parameters (McGuire and McDonnell, 2006).

The input files for this model are daily rainfall, daily stream and wetland outflow discharge, and isotope composition of rain and discharge. Therefore, results of the model are in days.

The Transit Time Distribution - TTD describes the integrated response of the time that each molecule of water takes to arrive at the catchment outlet from all locations in the catchment (McGuire and McDonnell, 2006). By integrating the results of the event analysis and the baseflow analysis through an exponential model, the TTD for individual events can be obtained. An exponential TTD is considered appropriate given that it is used for comparative purposes between the three studied catchments.

5.4. Results and discussion

Bi-weekly precipitation ranges from 6 mm to 357 mm distributed between the two annual rainy and the two dry seasons. The wet seasons are in the months of Oct-Nov-Dec and Mar-Apr-May and the dry seasons in the months of Jun-Jul-Aug-Sep and Jan-Feb. Precipitation bi-weekly isotopic composition has a corresponding seasonal fluctuation as can be observed in Figure 5-3, ranging from -3.2‰ to -20.2‰. The composition of $\delta^{18}O$ in the three streams follows the pattern of the precipitation composition although it is significantly damped ranging between -9.6‰ to -13.3‰. The minimum and maximum values correspond to the variation between the three streams.

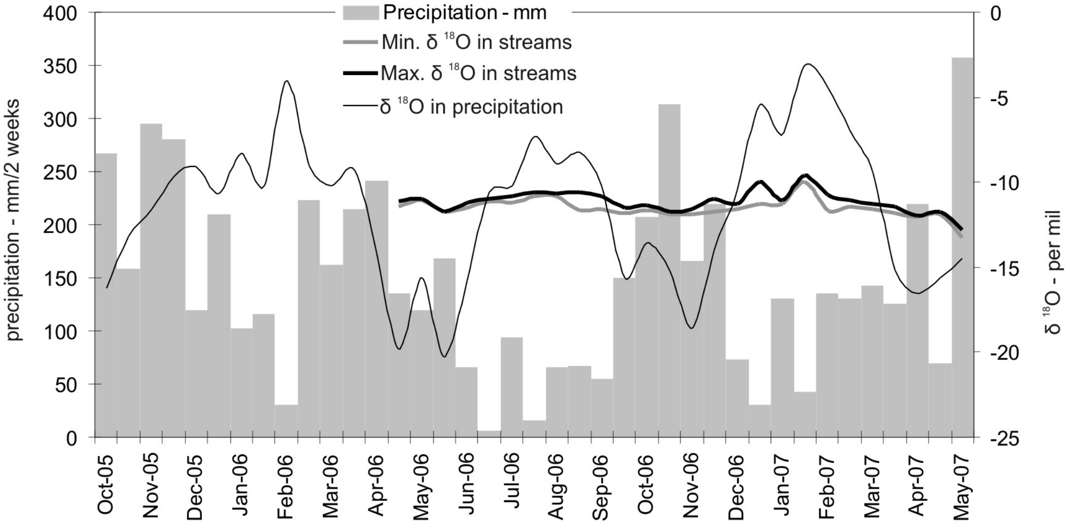

Figure 5-3 - Bi-weekly precipitation and corresponding δ ^{18}O; and range of δ ^{18}O measured in the three streams.

The isotopic composition of precipitation and the streams coming out of the six monitored catchments is given Appendix 11. The precipitation isotope composition is variable between events and the range of values for each event varies between only 0.3‰ for event 7 to 8.1‰ for event 2.

5.4.1. Response Time and Transit Time analysis

Results of the Transit Time model for the baseflow samples taken every two weeks are shown in Table 5-3. The three catchments have relatively high yields. Yield is defined as the proportion of rainfall that becomes stream discharge on an annual basis. B2, with a yield of 76% is the catchment with the smallest infiltration and storage capacity when it rains, and thus a larger proportion of rainfall becomes runoff. BB, despite having a similar percentage of forest cover than B2, has the lowest yield, pointing to the higher proportion of wetland area that would contribute to store water and preventing a higher proportion of runoff. BBW shows a low yield contributing to reducing BBS yield. B2W has a lower yield than its respective catchment although higher than that of BBW.

The mean response times of water in B2W and BBW are significantly longer than the ones in their respective catchments. The wetlands appear to hold water for a longer period than other components of the catchment. The mean response times indicate that the water that enters B2 catchment takes 28 days to reach the catchment outflow, being the catchment with the shortest mean response time; the water that enters B1 takes 97 days to leave the catchment and for BB catchment, the water takes 172 days to leave. The wetlands in BB could be the main explanation for the longer mean response time of water in BB (given that the mean transit time of BBW is almost 100 days longer than that of BBS transit time); and the forests in B1 could explain the intermediate response time of water for this catchment. However, a detailed analysis of the catchments topography could contribute to isolating the effect of land use on the mean response time of water. The separation of the input water into the slow and the fast compartments shows that it is the mean response time of the slow reservoir that is significantly shorter for B2 than for the other two catchments (50 days versus 500 days), which draws down the total mean response time for B2.

The total mean response time is influenced by the proportions of the fast and slow reservoirs in baseflow. The large proportion of slow reservoir for wetland BB (88%) combined with a long MRT for the slow reservoir (500 days), results in a long total MRT. Catchment B2, despite a relatively large slow reservoir portion, has a short MRT due to its short MRT for the slow reservoir.

Table 5-3 - Results of baseflow analysis (S = stream; W = wetland)

	B1S	B2S	BBS	B1W	B2W	BBW
Portion of fast reservoir	64%	37%	34%	n/d*	40%	12%
Portion of slow reservoir	36%	63%	66%		60%	88%
Mean Response Time (days)	97	28	172		170	270
Mean Response time - fast reservoir (days)	5	2	2		6	10
Mean Response time - slow reservoir (days)	500	50	500		493	500
Mean Transit time (days)	> 300	> 300	> 300		>300	276
Measured yield	68%	76%	62%		58%	15%
Simulated yield	72%	76%	63%		63%	17%
Q efficiency - mm/hr	0.62	0.57	0.59		0.66	0.12
Concentration RMSE (per mil)	0.82	0.89	0.79		1.22	1.17

* No results provided due to inconsistent isotope signal. Efficiency and root mean square error – RMSE indicate accuracy of simulation results.

As mentioned in the methods section, one possible obstacle for the estimation of the overall mean transit time is a short data record for the isotopic composition of discharge. Given that the obtained values for MTT are above 300 days, no differences between the catchments can be determined.

5.4.2. Pre-event water from headwater catchments

For this analysis an event is defined as the precipitation equal or larger than 2 mm that ends when there has been no precipitation for the following 2 hours. Based on the duration, the total precipitation and the 30 minute intensity of each event, five classes were identified, as shown in Appendix 3. This classification was constructed considering the distribution and differences found between the combinations of factors.

Five sampled storms were analyzed using TRANSEP for the three catchments and three corresponding wetland contributing areas. The results are shown in Table 5-4. Results include event water, defined as the proportion of stream discharge during an event that originates from precipitation; pre-event water defined as water that was held in a catchment prior to, and has been discharged into the stream during a storm event (Buttle, 1998); and runoff coefficient corresponds to the proportion of rainfall that becomes stream discharge during an event.

The pre-event water fractions of storm runoff for the wetlands average 46%, 73% and 82% for wetlands B1, B2 and BB respectively. The corresponding pre-event fractions for the catchments are 69%, 71% and 83%.

Pre-event water flowing out of the wetlands is highly influenced by the type of event (total precipitation, duration and intensity). The pre-event water discharge from wetland B1 is inversely proportional to the amount of rain of the event and it ranges from 14% to 81%. For wetlands B2 and BB, pre-event water discharge is also influenced by the antecedent precipitation; in drier periods, pre-event water is lower in both wetlands, although the range is much smaller than from B1. Wetland B2's pre-event discharge ranges from 65% to 95% and wetland BB's pre-event water ranges from 76% to 84%. On average the lowest pre-event water fraction among wetlands corresponds to B1 wetland, which has the lowest organic matter content and the lowest porosity. BB wetland has the largest pre-event water fraction explained by its large area that facilitates mixing of new and old water.

For the catchments, there is not a large difference between B1 (forest dominated catchment) and B2 (grassland dominated catchment), which have pre-event water of 69% and 71% respectively. Catchment BB however, has higher pre-event water of 83%, which could be linked to the presence of wetlands in 6% of the catchment area. Catchments B2 and BB are relatively similar in their runoff coefficients (21% and 27% respectively); while B1's is significantly lower (8%). Catchments B2 and BB have similar distribution of land coverage, with grasslands as the dominant land use (69% and 62% respectively) the difference being the percentage of wetland area (6%). The lower RC of B1 shows the significant effect of forests in the retention of rain events.

Similar studies done in tropical environments have shown mixed results in terms of the dominant source of event discharge. Goller et al. (2005) did a comparative study of three micro-catchments in the eastern slope of the Ecuadorian Andes at an elevation of 1900-2200 meters above sea level finding pre-event water contributing 19%, 56% and 22% to the total storm-flow runoff, making stream discharge event-dominated. It should be noted that for this study one single sample was taken immediately after one event for the three micro-catchments thus limiting the conclusiveness of the study. McCartney et al. (1998) studied one 330 ha catchment in Zimbabwe at an elevation of approximately 1,600 meters above sea level, with a dambo (seasonally saturated wetland) occupying 36% of the catchment area. They found pre-event water for two events to be 12% and 42% of total discharge, and that the larger the event, the greater the proportion of new water in the hydrograph. Johnson et al. (2007) studied a two ha forested catchment in the southern Amazon basin at an elevation of about 650 m above sea level, analyzing 14 events that averaged 79% of pre-event water.

In line with Johnson et al. (2007) and most studies done in temperate climates (Genereux and Hooper, 1998) the results of the present study show dominant pre-event water in the total event discharge at the catchment and wetland scales except for wetland B1 that has a more variable response and is the smallest catchment in the analysis.

Antecedent precipitation combined with the size of the event, are major factors in determining the percentage of pre-event water in the total discharge. For this reason it is reasonable to compare the events for similar antecedent precipitation conditions. Event 2 (Figure 5-4) is a good illustration of the differences between catchments B1 and B2 since antecedent precipitation conditions and the characteristics of the event were similar for the two catchments. Event 5 (Figure 5-5), allows a better comparison between catchments B1 and BB. The antecedent precipitation for the three catchments is relatively low and the event on B1 and BB is classified as one of medium size and high intensity.

Figure 5-4 summarizes the simulation results of the TRANSEP model for event 2 in the three catchments (B1 on the left column, B2 on the middle column and BB on the right column). The upper panels show the effective precipitation and the proportion that becomes event water. Note that the event was not spatially homogeneous and was classified as an event Type 5 in catchments B1 and B2 and Type 2 in catchment BB. The stream discharge and event water contribution are shown in the middle panel. Antecedent precipitation conditions are fairly similar for B1 and B2, as well as the event precipitation however B2's hydrograph shows a higher response, although the event water component for the two catchments is very similar (23% and 25% for B1 and B2 respectively). The larger discharge of catchment B2 could be linked to its relatively smaller proportion of area in forest.

BB's antecedent precipitation for 1, 2 and 7 days was higher than for the other two catchments which might explain the large volume of catchment BB's response and the high pre-event water contribution (88%), despite a smaller event (16 mm compared with 24 mm in the other two catchments). However, the effect of a 6% of area in wetlands should not be discarded as a source of pre-event water.

The bottom panels show the fraction of rainfall that becomes discharge in the stream (f) and the fraction of event water in the stream (X). For the three catchments, the fraction of rainfall that becomes stream discharge peaks during the highest rainfall intensity and declines very quickly, but the peak values are different: 33% for B1, 45% for B2 and 17% for BB. The fraction of event water in the stream shows very different patterns in the three catchments. During peak discharge, event water in B1 is 30% and declines steadily, while in B2 it reaches 28% but remains high for almost 8 hours after an initial short decline. In BB the fraction of event water in the stream starts at 15% and declines steadily.

For event 5, the hydrograph responses are distinct (Figure 5-5): B1 has a low peak flow response and 45% of event water; and BB has a high peak response and 14% event water. The main differences between the two catchments are the areas of forests and grasslands, with B1 being predominantly covered in forests and BB having a large percentage of grasslands and a 6% of wetlands. As can be seen in the map of Figure 5-2, most of the wetlands in BB are directly connected to the stream network which could be a factor facilitating the drainage of pre-event water into the main channel.

One commonality between the two events is the shape of the curves displaying the fraction of event water in the stream for each of the three catchments. These curves clearly show that catchment B1 initiates its discharge with a high proportion of event water that declines steadily once the rains have stopped; B2 increases its proportion of event water in the stream for several hours after the end of the rain; and BB discharges initially with a comparatively small proportion of event water and shows a slow decrease in the proportion of event water.

The accuracy of the simulation results is measured with two indicators: efficiency and root mean square error – RMSE, summarized in Table 5-4.

Efficiency corresponds to the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) for discharge, which measures the difference between the predicted values for discharge of the TRANSEP model against measured values, where an efficiency of 1 indicates a perfect prediction of the model in comparison with the measured values.

RMSE corresponds to the root mean squared error, is the measure of the differences between the predicted values of discharge by TRANSEP and the observed values. The smaller the RMES, the closer the predicted value is to the data.

Table 5-4 - Summary of simulation results of the TRANSEP model for the three wetland micro-catchments and the three catchments for 5 events.

Event	Catchment	total rain in event (mm)	event type	pre-event precipitation (mm) 1 day	2 days	1 week	Event water	Pre-event water	Measured RC	Simulated RC	Q Efficiency (mm/hr)	Q RMSE (per mil)	C Efficiency	C MRSE (per mil)	MTT hydrograph (hr)	MTT event (hr)
3	B1W	14	2	0	18	132	19%	81%	26%	26%	0.96	0.06	0.57	0.38	4.1	3.1
2	B1W	24	5	18	24	176	58%	42%	40%	40%	0.92	0.55	0.82	0.66	0.8	0.8
7	B1W	37	4	14	17	94	86%	14%	30%	30%	0.95	0.52	0.28	5.63	0.8	0.2
Average							54%	46%	32%	32%	0.94	0.38	0.56	2.23	1.9	1.4
3	B2W	14	2	0	13	122	5%	95%	3%	3%	0.97	0.01	0.36	0.23	1.5	1.3
2	B2W	24	5	16	17	144	19%	81%	6%	6%	0.81	0.04	0.72	0.37	2.8	2.7
7	B2W	14	2	22	24	94	35%	65%	27%	26%	0.92	0.06	0.80	0.77	5.6	3.3
Average							20%	80%	17%	16%	0.87	0.05	0.76	0.57	3.3	2.4
2	BBW	16	2	35	36	185	16%	84%	21%	21%	0.95	0.05	0.78	0.11	4.5	4.4
3	BBW	14	2	7	16	122	20%	80%	26%	25%	0.96	0.06	0.59	0.38	4.0	3.0
6	BBW	43	4	1	1	9	24%	76%	18%	18%	0.93	0.20	0.77	0.10	3.3	2.0
Average							20%	80%	24%	23%	0.95	0.06	0.69	0.25	3.9	3.1
5	B1S	17	3	2	20	51	45%	55%	5%	5%	0.62	0.04	0.57	0.85	3.4	2.7
2	B1S	24	5	18	24	176	23%	77%	10%	10%	0.95	0.04	0.68	0.43	4.0	3.3
7	B1S	30	4	14	17	94	32%	68%	5%	5%	0.54	0.10	0.86	0.73	6.1	3.7
6	B1S	38	4	2	2	17	24%	76%	11%	10%	0.85	0.12	0.63	0.16	3.5	2.2
Average							31%	69%	8%	7%	0.74	0.08	0.68	0.54	4.3	3.0
5	B2S	24	4	1	3	51	40%	60%	14%	13%	0.80	0.13	0.86	0.36	3.9	3.4
2	B2S	24	5	16	17	144	25%	75%	21%	20%	0.90	0.08	0.78	0.39	5.2	5.0
6	B2S	31	4	2	2	23	21%	79%	28%	27%	0.98	0.10	0.48	0.11	4.6	4.4
Average							29%	71%	21%	20%	0.89	0.10	0.71	0.28	4.6	4.3
2	BBS	16	2	35	36	185	12%	88%	25%	25%	0.96	0.05	0.48	0.21	4.4	3.9
5	BBS	16	3	1	6	35	14%	86%	19%	19%	0.76	0.11	0.59	0.25	4.4	3.4
3	BBS	21	4	7	16	122	27%	73%	36%	36%	0.95	0.09	0.88	0.30	3.2	2.5
Average							17%	83%	27%	27%	0.89	0.08	0.65	0.25	4.0	3.3

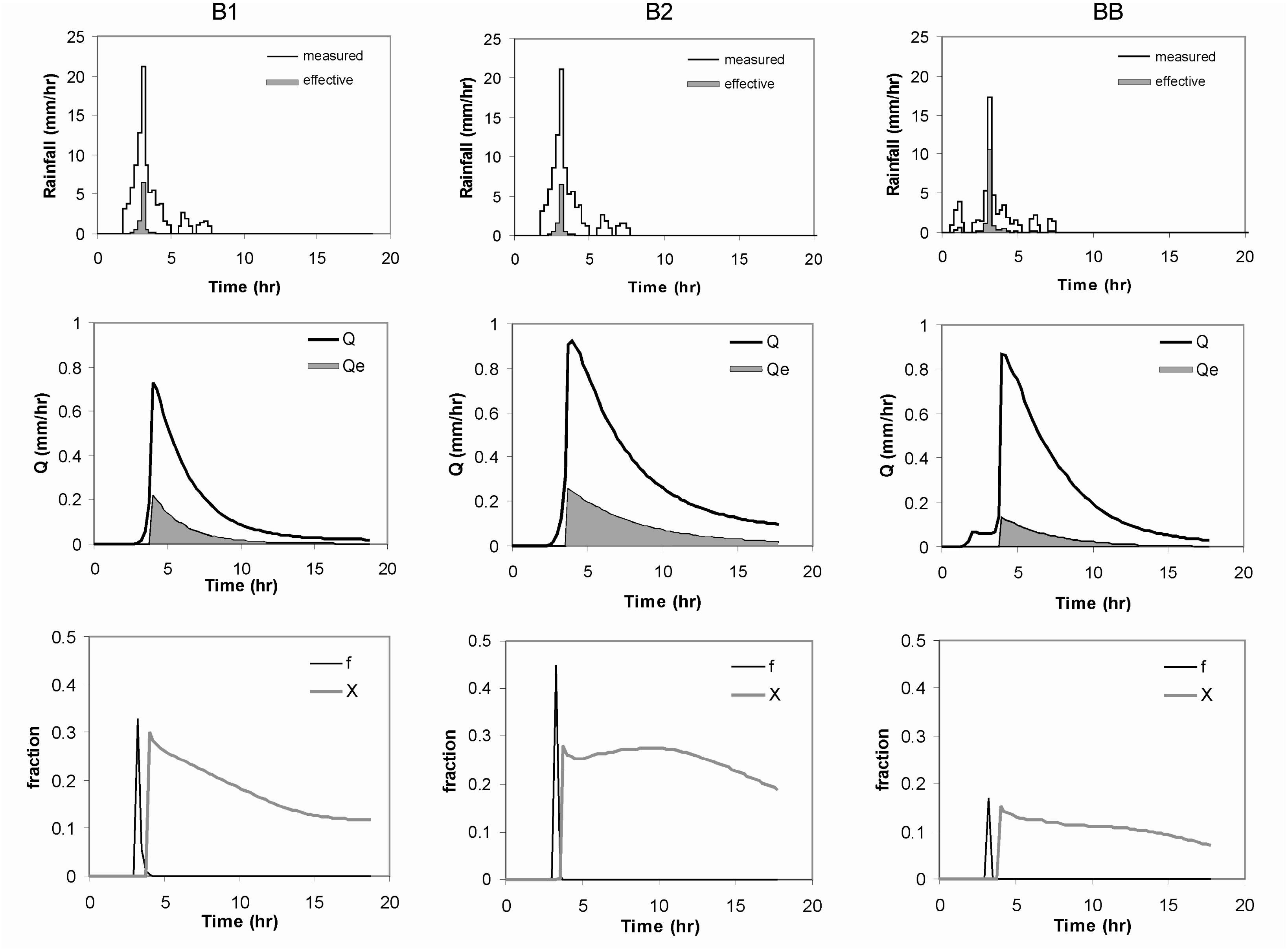

Figure 5-4 - (top) Measured and effective precipitation that produces runoff, (middle) simulated *Q* and event water discharge *Qe*, and (bottom) fraction of event water in effective precipitation *f* and fraction of event water in the stream *X*, for event 2 in catchment B1 (left column), catchment B2 (center column) and catchment BB (right column).

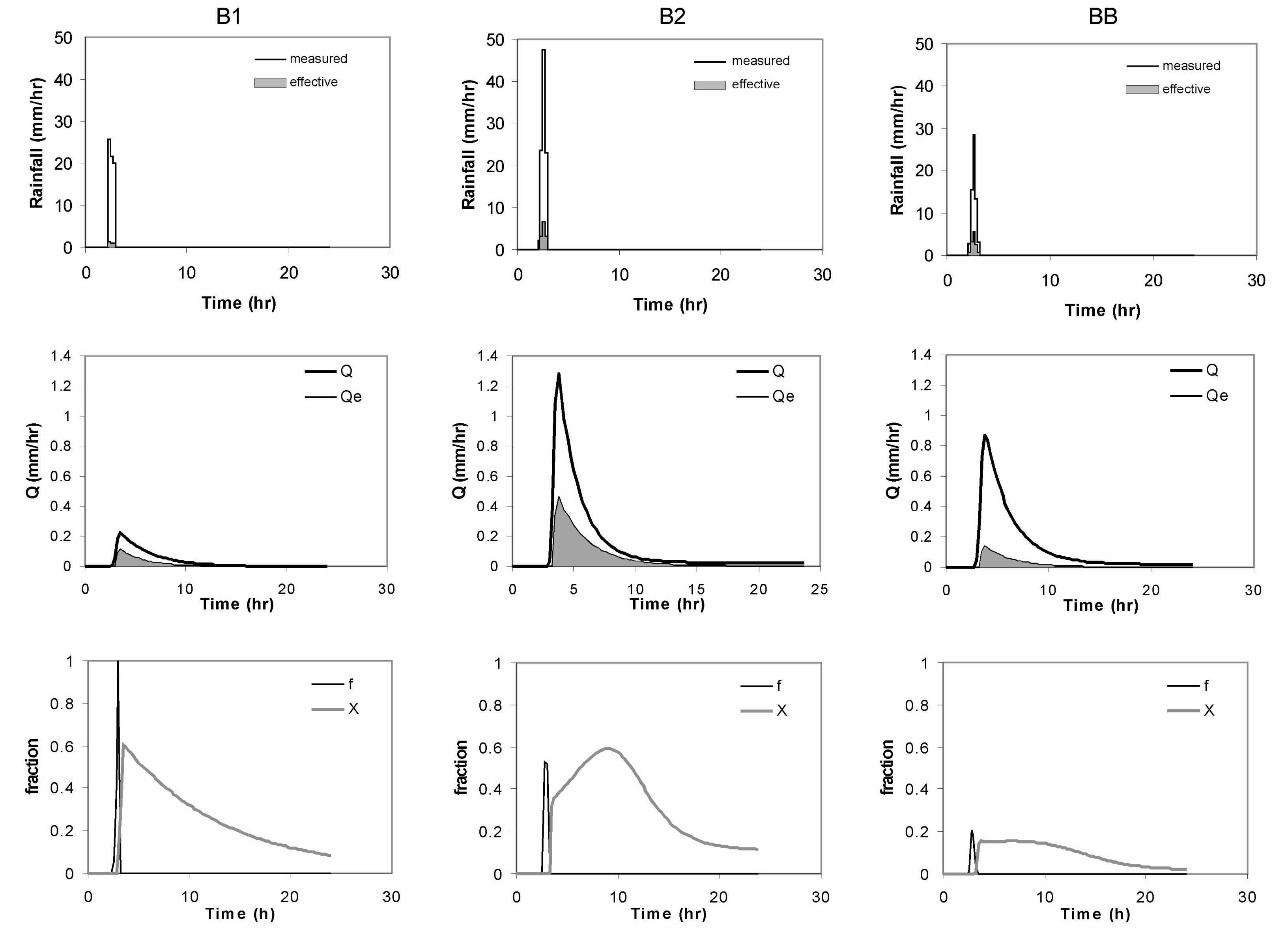

Figure 5-5 - (top) Measured and effective precipitation that produces runoff, (middle) simulated *Q* and event water discharge *Qe*, and (bottom) fraction of event water in effective precipitation *f* and fraction of event water in the stream *X*, for event 5 in catchment B1 (left column), catchment B2 (center column) and catchment BB (right column).

5.4.3. Runoff coefficient

The runoff coefficient (Table 5-4) is an indicator of the capacity of a catchment to attenuate stormflow. The runoff coefficient is highest for wetland B1 (average 32%) which suggests a limited water holding capacity. The smaller runoff coefficient for B1 catchment in comparison with the other two catchments, points towards the contribution of forests in holding water during events, since the area under forest in B1 is 68%.

5.4.4. Mean Transit Time – MTT of event water and Transit Time Distribution - TTD

The last two columns of Table 5-4 give the mean transit time of water for particular events for each of the wetlands and catchments. The first of the two columns represents the transit time of the catchment to the entire volume of water that becomes stream discharge. The second column represents the response time of the catchment to the water that falls as precipitation during that particular event, that is, the time during which event water flows out of the catchment outflow. Since the event water that becomes discharge is a portion of the overall discharge water of the event, the response time of the event water is always smaller than the hydrograph response time. The smallest difference between hydrograph and event mean transit time corresponds to catchment B2, where MTT of the hydrograph is only 7% larger than the MTT of the event water; this can be explained by the reduced water holding capacity of the catchment which translates into event water flowing during most of the time that the total discharge occurs. The largest difference is observed for catchment B1 with 43% difference explained by the large water holding capacity of the forests in this catchment.

The comparison between the TTDs for events 2 and 5 are shown in Figure 5-6. Event 2 is similar for catchments B1 and B2 in terms of the magnitude of the event and antecedent precipitation. For both catchments the event is large and long (type 5) and one-week antecedent precipitation is high. The TTDs show that both catchments have a similar pattern, but for B2, a higher portion of event water leaves the catchment in the first 20 days after the event. The behavior of catchment BB, reveals the effect of saturated conditions on this catchment. Even with an event classified as type 2 (medium size with low intensity), the high antecedent precipitation for one day, two days and one week causes a significant discharge of event water within the first few hours after the event. This can also be observed in Figure 5-4. Since the rainfall that becomes discharge is relatively low for catchment BB in this event, a large portion of this water (88%) is pre-event water. Similar antecedent precipitation conditions are experienced by B1 for this event, and even with an event type 5, B1 does not present a response as large as BB.

Event 5 provides a good comparison between catchment B1 and catchment BB, since this event is a medium size event of high intensity for both catchments and they had similar antecedent precipitation conditions. What explains the higher proportion of short transit time for catchment B1 is the high maximum intensity during this event (12 mm in 15 minutes) which is the highest intensity reported in the events analyzed. After approximately 12 hours, catchment B1 significantly reduces the proportion of fast passing tracers. Catchment BB, in response to a medium size event after relatively low antecedent precipitation conditions, responds with a TTD with a gentle slope. For catchment B2, this event was classified as event type 4, large and intense. The response of this catchment to this event was characterized by a steep TTD with the largest concentration of fast tracers during the first 10 days after the event, among all the events analyzed.

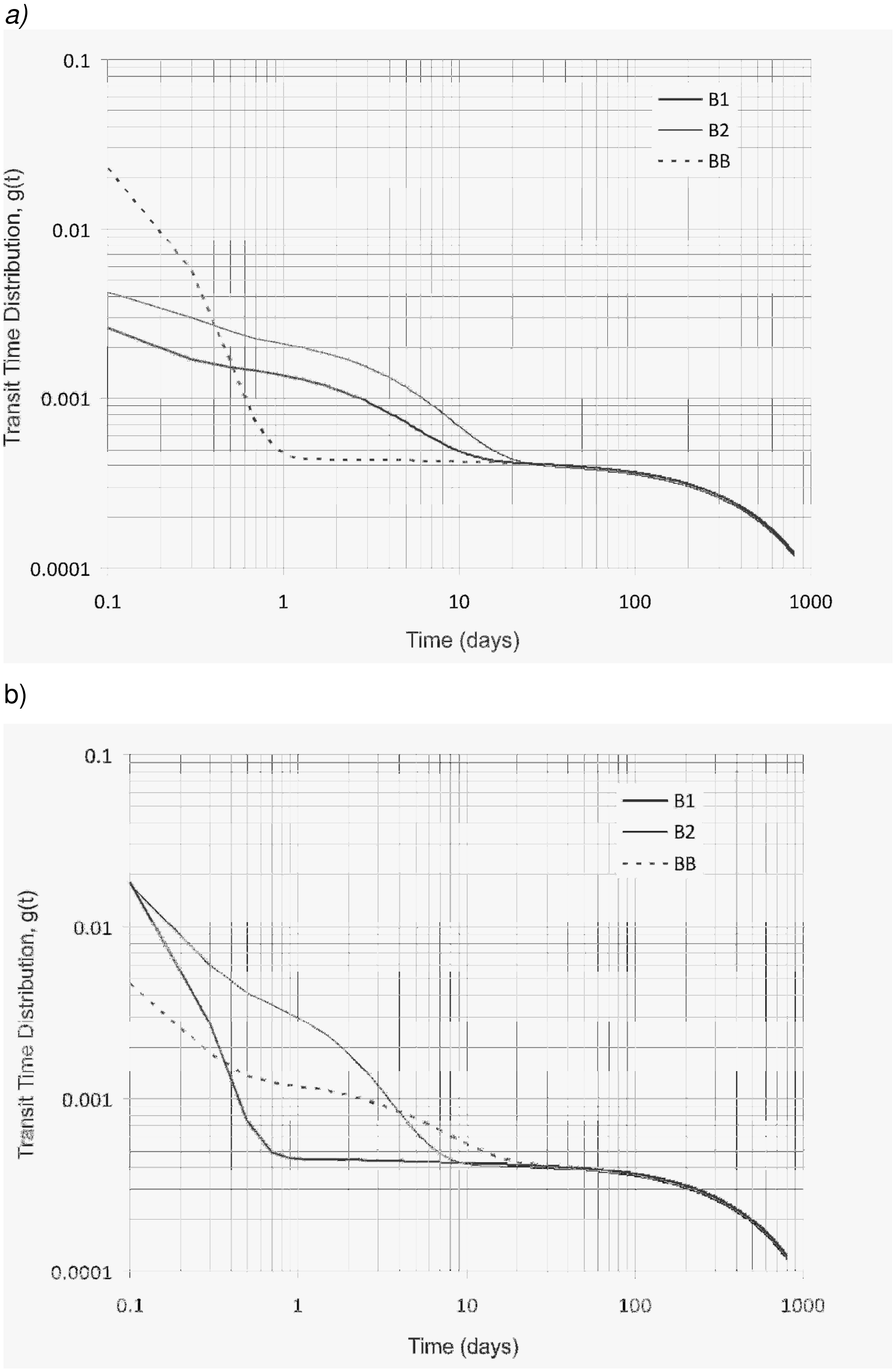

Figure 5-6 - Transit Time Distributions for the three studied catchments: a) for event 2; and b) for event 5.

5.4.5. Sources of discharge and transit time of water in headwater catchments

The comparison of three neighboring catchments with similar topography and size allowed establishing differences in terms of the proportions of fast and slow sources of water in baseflow and the time that water spends in each catchment. Results indicate that for B1, the catchment with 68% of area in forest, discharge comes predominantly from the fast reservoir (64%) with a response time of five days, whereas for the other two catchments, the fast reservoir constitutes between 34% and 37% of total baseflow and have a response time of 2 days. The mean response time of water in catchment BB, 172 days compared with 97 days for B1 (the forested catchment) and 28 days for B2 (the catchment with 69% in grasslands) is influenced by the longer transit time of BBW and B2W. The small runoff coefficient determined from the hydrograph separation analysis of BB provides an idea of the storage capacity of this wetland relative to the other two wetlands studied.

The difference in the resulting yields for each catchment provides an idea of their general water holding capacity. Catchment B2, with a larger proportion of grasslands, had the highest yield. This may be explained by lower rates of infiltration in compacted soils under grazed grasslands that produce higher rates of stream discharge during rain events. In general, it appears that a 6% of area in wetlands makes a contribution to reducing yield in catchment BB. Lower RC for individual events contribute to reducing the overall yield of this catchment.

5.4.6. Water storage and storm flow attenuation

The comparative analysis of three wetland micro-catchments and three headwater catchments with the use of oxygen isotopes for hydrograph separation of event discharge is a useful tool to understand the differences that land use has on water flow regulation and the source of water during storm events. Two main findings arise from this comparison: 1) the grassland dominated catchment B2 has a higher event response in relation to the forest dominated catchment B1, but both of them show a similar composition of event and pre-event water; and 2) even a small percentage of area in wetlands (6% of catchment area for BB) drain a high percentage of old water during storm events related to the higher connectivity of saturated areas to the discharge network.

The first conclusion implies that in general, the storage capacity of forests and soils under forests is higher, but during an event old water is pushed out of wetlands in a higher proportion than from riparian and natural forests.

The comparison of the isotopic analysis for baseflow and for events indicates the differences in hydrological response at different time scales. The baseflow analysis has a longer time scale (1.5 years) and the event analysis takes individual storms. The results of the event analysis for runoff coefficient - RC (from the Isotopic Hydrograph Separation Model) corresponds to only five events. The comparison showed that BB is the catchment with the lowest yield at the baseflow scale and B1 is the catchment with the lowest RC at the event scale.

The TTD illustrated the differences in the capacity of catchments to store storm events. Catchment BB, probably as a consequence of its area in wetlands, presented a “breaking” or “bursting” behavior when the antecedent precipitation was large, even for a medium size event. B1 on the other hand, even during a large event that occurred with high antecedent precipitation, presented the slowest TTD.

5.5. Conclusions

Isotope applications in hydrology have been used to understand hydrological processes with the goal of providing information to modelers about the way water moves in a catchment. This study has used the isotope approach to compare the effects of land use on stream discharge and water composition, in order to provide water purveyors with information that can be used to protect their water source.

Wetlands are catchment components where water is stored for longer periods of time than in other catchment compartments, prolonging the mean response time of water in their catchments and reducing annual yields. Forests soils also appear to increase the response time of water but to a less extent than wetlands. The study would have benefited of a topographic comparison of the catchments to isolate the effects of land use on hydrologic response.

The discharge from the three catchments is dominated by pre-event water and land use differences do not appear to influence this. Forests seem to reduce the runoff coefficient and wetlands respond differently depending on their topography, antecedent precipitation and the type of event. Wetlands retain water for a longer period of time than other catchment compartments but during events, their water retention depends on their previous saturation.

The distinct response of catchments to rain events was demonstrated through various indicators. The fraction of event water in the stream discharge provides evidence of the larger holding capacity of catchment B1 and BB in comparison with B2; consistent with these findings, TTDs showed the significant importance of antecedent precipitation conditions in determining the type of response of catchment BB, which is characterized by a high water holding capacity (low RC and low yield). When this catchment is exposed to medium to large events in conditions of high antecedent precipitation, it has a “bursting” behavior. The TTD of catchment B1 showed that even for large and long events, this catchment retains water for longer periods of time in contrast with B2.

Wetlands display two distinct behaviors. On the one hand they appear to increase the response and transit time of water in catchments on an annual basis and reduce annual yields. But in times when precipitation is high and intense, they contribute to augment flows as demonstrated by the response of catchment BB to event 2. The forested catchment has a more consistent behavior, showing that even for large events it has a capacity to ameliorate storm flows.

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6. Summary and synthesis

6.1. Summary

The goal of this research was to determine the hydrological dynamics of three small headwater catchments that contain wetlands and are located in the tropical Andes of Colombia. The catchments occupy a total area of 400 ha and the three streams are a major source of water for a community of 15,000 people. The specific aims of the research were to:

- Determine the hydrological regime of wetlands and examine the contributions they made to regulating seasonal, annual and storm flows.
- Examine the differences of the three catchments and determine how the key factors of land use, site conditions and wetlands, influence their hydrological response.
- Quantify the transit and the response time of water in the catchments using isotope tracers.
- Analyze the integrated rainfall – runoff processes at the wetland and catchment scales, to understand water availability fluctuations and the mechanisms of water scarcity and storm runoff.

The catchments, named B1, B2 and BB, are part of the headwaters of the Barbas river, which belongs to La Vieja river flowing to the Atlantic Ocean. The headwaters are adjacent to each other, at altitudes between at 2,000 – 2,200 m of elevation, and are similar in terms of size, morphology, geology and climatic conditions. They differ in terms of land use. B1 is predominantly a forested catchment (68% of its area is riparian or natural forest), B2 is dominated by grasslands (69%) and BB is different from B2 in that it has a 6% of wetlands.

6.1.1. Precipitation regime and variability

The average annual precipitation over the 3 year study was 3000 mm and the rainstorm events were classified into 5 categories based on intensity and duration. More than 50% of the rainstorms were of small size (< 10 mm) while 10-20% of the rainstorm events were large events of short duration (< 5 hours) producing 30-40% of the annual rainfall. Few storms were observed of large precipitation and long duration. There were two wet seasons from April-May and October-November followed by two dry cycles from December-February and June-August (Poveda et al., 2006). The spatial variability between the three catchments was moderate on an annual basis but reached up to more than 50% during individual storm events.

6.1.2. Critical soil characteristics

The soils in the three headwater catchments were classified as Andisols developed on fluvio-volcanic clay parent materials. They have low storage-release coefficient (high water holding capacity combined with a poor release capacity) and remain moist during most of the year. The average soil moisture differences between the wet and dry season was only 12% for riparian and natural forests, 8% for grasslands and 7% for plantation forests. Because of the unusual water storage and release characteristics of these Andisols they influence the hydrological processes by creating slow percolation rates and increased surface runoff during the wet season. Both the soil moisture content in the field and the soil moisture curves indicate that the soils under riparian and natural forests have a larger capacity to release water than those in grassland.

6.1.3. Wetland hydrology

The three wetlands were of different size (B 1= 1,070 m^2, B2 = 550 m^2 and BB = 6,650 m^2) and showed very different hydrological responses. All three wetlands stopped producing surface outflow during the dry season and no relationship could be found between wetland area and volume discharge. On a per unit area basis, B2 had a more sustained flow as indicated by the flow duration curve (FDC). BB wetland had a higher discharge (m^3/month) than the other two wetlands, but all values are small and none made a significant contribution to dry season flow. Potential evapotranspiration rates were calculated to be between 0.04 – 9.3 mm/day. Despite the high annual precipitation, the high potential evapotranspiration during the dry season, contributed to water deficits in all three wetlands. According to the monthly discharge of wetlands, wetland BB produces a “burst” effect at the end of the large rainy season.

6.1.4. Factors influencing wetland hydrology

The wetlands in the study area occupy only a small portion of the catchment area, yet their influence in small catchment hydrology was quantifiable. In terms of water volume, the contribution of these wetlands to baseflow in the dry season is significantly small. Based on the analysis of the surface discharge, the volume of water that flows out of the wetlands is negligible in comparison with the discharge of their host catchments and in relation to the water use of the communities downstream. In terms of water discharge per unit area, one of the three monitored wetlands (B2) had a higher yield than its host catchment during part of the dry season. This wetland is characterized by a portion of its area as open water with no vegetation and a surface outflow. Out of the total number of wetlands (52) in the catchments only five wetlands with a total area of 0.9 ha have these properties, and of these three are located in catchment BB with an area of 0.7 ha.

A threshold in wetland area was found below which limited rain water retention occurred. BB, the largest monitored wetland (0.6 ha.) is the only wetland that consistently shows a lag in time between the peak in rainfall and the peak in wetland outflow. Of the 52 wetlands in the inventory, only three wetlands are of this size or larger. The characteristics of the storm (intensity and duration) combined with the antecedent rainfall also influence wetland outflows and time lags; wetland BB in conditions of high antecedent precipitation showed a “bursting” behavior. Wetland size contributes to increase lag times but this capacity is reduced under intense precipitation. Given that intense events comprise approximately 35% of total precipitation, short lag times between the peak in rainfall and the peak in flow are common.

Size in the studied wetlands however does not influence the water volume response of wetlands to rain events (Roa-García, et al., chapter 3).

6.1.5. Catchment hydrology regime

Annual water yields for the three catchments were quantified as 74% for catchment B1, 82% for catchment B2 and 65% for catchment BB. The FDC of the three streams showed that B1 and B2 display similar behavior during 60% of the time when the flows were high. When the flows were reduced in the dry season, the flow in B1 decreased first. However, when the dry season advances, B2 showed a significant drop in flow. In the dry season B1 presents a significantly reduced flow, though still an order of magnitude higher than flow in B2. B2 had a discharge in the dry season opposite to what the annual water yield showed. BB had a smaller discharge in the medium range of flows in relation to the other two streams which explained why the annual water yield was smaller, but in the dry periods (10% of the time) the flow was higher than the other two streams. BB was the stream that sustained flow the longest in the dry season. Its flow only dropped below B1 during the end of the dry season.

The response of catchments to individual storms showed that there are no significant differences in discharge coefficients of the three catchments for small or medium size events. B1 is the catchment with the lowest discharges during all event types and seasons. Catchment B2 shows significantly higher flows for all types of events and the highest maximum values of discharge. This makes apparent the influence of forests in reducing discharge during rain events (B1); and the possible “bursting” effect of wetlands during intense and/or large events that could increase the discharge of the host catchment (BB). The lags from peak precipitation to peak discharge for the three catchments showed that catchment size has no major influence in lag times.

Lumped lag times do not show significant differences between the peak in rain event and the peak in discharge for the dominantly forested catchment (B1) and the dominantly grassland covered catchment (B2). They contrasted with the linear reservoir analysis that showed a slower release of water for catchment B1. This indicates that both catchments have a synchronized peak but the rate of water release is different, the forested catchment having a slower release of water. Despite the smaller size of catchment BB, there is a delayed effect of peak rainfall and water release. BB is also the catchment with the smallest average discharge coefficient, although discharge for intense and/or large event is larger than for the other two catchments.

6.1.6. Factors influencing catchment hydrology

Although the research project had a focus on wetlands, the large difference in area of forest between the three studied catchments, allowed conclusions to be drawn on the effects of forests on catchment hydrology. The comparison of the seasonal distribution of flows (monthly water yield) and FDC showed that the catchment with the highest percentage of area in grasslands (69%) was the catchment with the highest annual water yield particularly in the rainy season. The catchment with the highest percentage of area in forest (68%) experienced a small reduction of flow during the dry season, and maintained a higher flow during the last days of the dry season in comparison with the grassland dominated catchment. These two findings support the “infiltration trade-off” hypothesis for tropical environments; that soils that are subject to compaction (such as highly grazed grasslands) have a reduced rainfall infiltration, which impairs the maintenance of baseflows. In the dry season the forest demand for water was estimated to be around 28% higher than that of grasslands. The calculation of PET for each catchment could help explain why the FDC for B1 showed lower flows per unit area than B2 for the flows corresponding to the beginning of the dry season.

The effects of wetlands on catchment hydrology are indicated by the FDC. Catchment BB was found to have a smaller discharge by unit area in the medium range of flows in relation to the other two streams, which explains why the annual water yield is smaller. But in the dry periods (10% of the time) the flow per unit area is higher than in the other two streams. Its flow only drops below the flow of B1 during extremely dry periods. A 6% wetland area in BB, a small catchment, could be a factor contributing to the maintenance of low flows. The comparison of water yields between wetlands and catchments points to the characteristics of wetlands that influence the hydrological behavior of the host catchments. B2, a permanent wetland with a surface outflow and a portion of its area as an open water surface, produced a water yield in the dry season that is slightly higher than the water yield of the host catchment. A wetland with a surface outflow and an open water surface (similar to B2 wetland), but 10 times larger (0.5 ha), located in catchment BB might explain why this catchment has higher flows in the driest periods in comparison with the other two studied catchments.

The linear reservoir concept allowed the comparison of the residence time of water during an event. The results indicated that water required more time to leave the forested cacthment, but that wetlands have a significant effect in prolonging the residence time. Even though catchment BB had higher discharge coefficients for large events, the linear reservoir concept showed that on a per unit area basis, water took more time to leave BB in relation to the other catchments.

A detailed analysis of topography would be required to quantify the differences in potential storage of water between the catchments. Differences found in the hydrological response of the catchments, could be the result of the combined effect of topography and land use. The assumption that the topography is similar for the three catchments is however reasonable given that the catchments are within the same geological unit and are within the same elevation range (Roa-García, et al., chapter 4).

6.2. Synthesis

Results from the hydrological analysis, transit time model and isotopic hydrograph separation are summarized and compared in Table 6.1.

Wetlands appear to prolong the response time of water in their catchments (the time the catchment takes to respond to rainfall). On the basis of the transit time model results, response time of wetlands B2 and BB is significantly longer than the response time of the catchments. Correspondingly, the response time of catchment BB, with the highest proportion of wetland area, has a significantly longer response time than the other two catchments. This analysis also indicated that total water yield was higher for B2, the catchment predominantly covered by grasslands, and is consistent with the hydrological analysis of annual discharge.

The relative ranking of the three catchments according to yield puts B2, the grassland dominated catchment as having the largest yield, and BB the catchment with the largest percentage of wetlands, as having the smallest yield. This relative ranking coincides with the ranking done through the calculation of discharge coefficients for a large number of events of all types. Both approaches indicate that BB catchment releases a smaller proportion of precipitation inputs.

However, when medium to large size events occur after several days of high precipitation, wetlands tend to “break”, reducing the transit time of water. This conclusion is based on the transit time distribution – TTD that is determined by combining baseflow and event isotopic parameters. The predominantly forested catchment had a higher storm amelioration capacity. Even for large events on high antecedent precipitation conditions, this catchment had a flatter TTD (Roa-García, et al., chapter 5).

Table 6-1 - Comparison of the hydrological analysis, transit time model and isotopic hydrograph separation

	Hydrology – all events	**Transit time model – Baseflow**	**Isotopic hydrograph sep. - 5 events**	
Wetland	**DC**	**Yield**	**RC**	**Event water**
B1	28%	n.d.	32%	54%
B2	18%	58%	17%	20%
BB	10%	15%	24%	20%
Catchment				
B1	22%	68%	8%	69%
B2	24%	76%	21%	71%
BB	20%	62%	27%	83%

DC – discharge coefficient; RC – runoff coefficient

Results of the isotope analysis of storm events show that the grassland dominated catchment B2 has a higher runoff coefficient - RC in comparison with the forest dominated catchment B1, but both of them show a similar composition of event and pre-event water. Even a small percentage of area in wetlands (6% of catchment area for BB) drain a high percentage of old water during storm events due to the higher connectivity of saturated areas to the discharge network (Roa-García, et al., chapter 5).

The overall findings of this research in relation to the contribution of wetlands to catchment hydrology are consistent with the body of literature in the field. Divergent conclusions about the role of wetlands were found. In terms of the contribution to baseflows, only wetlands with certain characteristics such as a portion of their area as an open water surface with no vegetation and a surface outflow, contribute to augment catchment low flows. The connectivity of the wetland to the stream via a surface outflow is a critical factor, as well as the existence of an open water surface that facilitates the flow of water. This characteristic of wetlands for baseflow contribution might also influence the way wetlands respond when their water storage capacity is full. An open water surface, connected to the stream network would facilitate the discharge of a large portion of the reservoir if the soil and vegetation that hold the water, cedes to the pressure of a full reservoir. For the attenuation of large rain events, a large wetland area and a relatively flat topography in the contributing area are factors that were conducive to storm flow reduction (Roa-García, et al., chapter 3).

The significant difference in area of forest between the studied catchments allowed the quantification of the influence of forests in small catchment hydrology. This study provides evidence of the infiltration trade-off hypothesis. Based on yield analysis, discharge coefficients, FDC, and two approaches of water isotope composition analysis, it was shown that although forests compete for water during the dry season, their soils contribute to sustaining baseflows.

6.3. Implications for management

Results of the hydrological and isotopic study show the dependency of the water providers on the ability of the ecosystems in the headwaters to regulate water flows. The relatively poor infiltration and release of water in the soil, amplify the differences in land use effects on the stream flow regulation. The transformation of the headwater catchments from forests and wetlands to grasslands is most likely contributing to the reduction in their water regulation capacity, as indicated by the soil moisture curves. Although the wetlands contribute to prolong the transit time of water in the catchments, their current water storage capacity does not compensate for the naturally limited availability of water in the catchments soils.

On the water demand side, in Filandia in particular and in Colombia in general, tariffs have already had an effect on reducing water use. Urban water use in Filandia has been reduced in the last few years at the same pace as in major cities in Colombia. Filandia's total water use, including agricultural use, is low compared with the consumption in other countries (Roa-García, et al., chapter 2).

With the current water use in Filandia, the water available in the streams in 2006 and the average water losses (leakages) for the two water providers, it was estimated that during 14% of the year, the water concessions are above the water flow in the streams. Assuming no restriction on withdrawals of water from the streams, and the flow characteristics and water use for 2006, reservoirs with a capacity of 4,500 cubic meters would be required to prevent water scarcity during the dry period of August and September. However, if the streamflows are reduced by 5% and demand increased by 2%, a reservoir of more than 6,700 m^3 would be needed to prevent water scarcity. This calculation is being used by the urban water provider to design a project to be presented for funding under the Regional Water Plan.

Acquiring the land for source protection and building reservoirs in these headwater catchments for water provision could be incorporated in the watershed management plan that has already been initiated for La Vieja River, the river basin in which the studied catchments are located.

The comparative hydrological and isotopic studies conducted in the three catchments have demonstrated the role that forests play in regulating water availability mainly through their effect on soil properties. The role of wetlands depends on their characteristics and location in the catchment. Only wetlands with an area of more than 550 m^2 and good connectivity to the stream network through an open water body appear to make a contribution to baseflow.

Overall the catchment soils with a low storage-release coefficient are not large contributors to stream flow. This makes it even more relevant to preserve the catchment units that contribute to flow regulation and suggests to CARs the need to re-evaluate concessions based on the capacity of the catchments to regulate water flows in time, more than on annual modal flows.

The limited water availability in dry seasons and the high demand for water, make it necessary for water purveyors to store water and avoid private water storage on individual farms, which conflicts with the principle of equal access to water. For small mountain municipalities such as Filandia with the majority of its population in the lower income level groups, funding for storage and distribution infrastructure and the acquisition of land for water source protection should come from regional and national sources, as is intended through the Regional Water Plans. Civil society groups can initiate the enforcement of Law 99 of 1993 in relation to the investment of municipalities in the protection of water sources by including these investments in the watershed management plans. Until the incentives and resources are available to build and manage reservoirs, conservation of these systems is important.

References

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Roa-García, C., Lavkulich, L., Brown, S. Chapter 3: Water flow characteristics of small wetlands in headwater catchments of the Colombian Andes.

Roa-García, C., Schreier, H. Chapter 4: Land use, wetlands and water flows in small headwater catchments of the Andes.

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Appendix 1. Calculation of the monthly Water Scarcity Index – WSI for the municipality of Filandia

The National Institute of Hydrology and Meteorology – IDEAM has lead the implementation of the water scarcity index to be calculated by the CARs for the watersheds where water has been granted in concessions, to estimate the vulnerability of the population relying on these catchments that are exposed to water scarcity. The index is calculated with the equation:

$$I = \frac{D}{O_n} \times 100\%$$

where D corresponds to water demand, and O_n corresponds to net availability of water. O_n is calculated by:

$$O_n = O_t \times (1 - (R_e + R_{it}))$$

where O_t corresponds to total availability of water (mean flow during the period for which the index is being calculated); R_e corresponds to the reduction of water availability to minimum flows and it is calculated as the percentage of the flow that is surpassed 97.5% of the time (calculated using the flow duration curves) over the mean flow for the period of interest; and R_{it} corresponds to the reduction of flow due to its temporal variation and is calculated using the variation coefficient and asymmetry of flow. IDEAM suggests Table 7 to facilitate the estimation of R_{it} according to the variation coefficient (Cv).

Table 10. Scale of water availability reduction due to temporal variation

Cv	**R_{it} (%)**
0 – 0.2	15
0.2 – 0.3	25
0.3 – 0.4	35
0.4 – 0.6	40
> 0.6	50

Taking an approximate value of R_e for the three streams of 0.5% which is the lowest annual for the three streams; and estimating a R_{it} at 15%, the water scarcity index per month is calculated.

Non-revenue water or water that is taken from the stream and treated but lost in the distribution system for ESAQUIN is estimated by the provider to be 25% for 2007. There is no data for RR, although it is estimated at around 40%.

Appendix 2. Calculation of Potential Evapotranspiration

Air temperature measured with a HOBO Pro© sensor connected to a data logger installed inside a solar radiation shield at the climate station mounted on a wooden post at 2 meters above the ground. The sensor has an accuracy of +/- 0.174 °C.

Relative humidity monitoring was recorded using a HOBO© relative humidity sensor with a range from 0 to 100% RH, mounted inside the same solar radiation shield where the air temperature sensor was located.

Wind speed was registered daily using a totalizing anemometer, readings are recorded daily at 7 am to give 24-hour wind run.

Solar radiation was recorded with a Silicon Pynanometer smart sensor© with a measurement range from 0 to 1,280 W/m2 and an accuracy within ±10 W/m2 or ± 5%, whichever is greater in sunlight; additional temperature induced error ± 0.38 W/m2/°C from +25 °C; with resolution of 1.25 W/m2 (Onset Computer Corporation 2003).

These variables were used to estimate potential evapotranspiration - PET, which represents a hypothetical upper limit to actual evapotranspiration (Moore, 1999). PET was calculated using the Penamn combination equation reproduced from Dunne and Leopold (1978) as follows:

$$PET = ((\Delta/\gamma)\ (H-G) + Ea)/((\ \Delta/\ \gamma) + 1)$$

where PET is the potential evapotranspiration in cm/day, γ is the psychometric constant in kPa /ºC, H and G are net radiation and soil heat flux, respectively, in mm/day of evaporation calculated by dividing the flux (W/m2) by the latent heat of vaporization, and Ea is the mass transfer evaporation rate in cm/day. The slope of the saturation vapor pressure versus temperature curve (Δ) is given in kPa /ºC by the slope of the saturation vapor pressure versus temperature curve (Δ) is given in mb/ºC by

$$\Delta = (4098\ e_{sa}) / (237.3 + T)^2$$

where e_{sa} is the saturation vapor pressure in kPa and T is the air temperature in ºC.

As saturation vapor pressure is related to air temperature, it can be calculated from the air temperature. The relationship is expressed by (Allen, et al., 1998):

$$e^{o}(T) = 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right]$$

where

$e°(T) = e_{sa}$

$e°(T)$ saturation vapor pressure at the air temperature T [kPa],

T air temperature [°C],

exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

This parameter is calculated for the average day temperature.

The net radiation, H, is the difference between incoming and outgoing radiation of both short and long wavelengths. It is the balance between the energy absorbed, reflected and emitted by the earth's surface or the difference between the incoming net short-wave and the net outgoing long-wave radiation. H is normally positive during the daytime and negative during the nighttime. The total daily value for H is almost always positive over a period of 24 hours, except in extreme conditions at high latitudes (Allen et al., 1998). The soil heat flux, G, is the energy that is utilized in heating the soil. G is positive when the soil is warming and negative when the soil is cooling. Although the soil heat flux is small compared to H and may often be ignored, the amount of energy gained or lost by the soil in this process should theoretically be subtracted or added to H when estimating evapotranspiration (Allen et al., 1998).

The conversion from energy values to depths of water or vice versa is given by (Allen et al., 1998):

$$\text{Radiation}[\text{depth of water}] = \frac{\text{Radiation}[\text{energy/surface}]}{\lambda \rho_w}$$

where

λ latent heat of vaporization [MJ kg^{-1}],

ρ_W density of water, i.e., 1000 kg m^{-3},

[depth of water] is expressed in m,

[energy/surface] is expressed in MJ m^{-2}.

By using a single value of 2.45 MJ kg^{-1} for λ and multiplying the above equation by 1000 to obtain mm:

$$\text{Radiation}[\text{mm day}^{-1}] \approx \frac{\text{Radiation}[\text{MJ m}^{-2}\text{ day}^{-1}]}{2.45} = 0.408 \times \text{Radiation}[\text{MJ m}^{-2}\text{ day}^{-1}]$$

The psychrometric constant, γ, is given by (FAO, 2000):

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P$$

where

γ psychrometric constant [kPa °C-1],
P atmospheric pressure [kPa],
λ latent heat of vaporization, 2.45 [MJ kg-1],
c_p specific heat at constant pressure, 1.013 10-3 [MJ kg-1 °C-1],
ε ratio molecular weight of water vapour/dry air = 0.622.

The specific heat at constant pressure is the amount of energy required to increase the temperature of a unit mass of air by one degree at constant pressure. Its value depends on the composition of the air, i.e., on its humidity. As an average atmospheric pressure is used for each location, the psychrometric constant is kept constant for each location.

P is given by (FAO, 2000):

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26}$$

where

P atmospheric pressure [kPa],
z elevation above sea level [m]

For an elevation of 2,100 meters (the three monitored wetlands are at 2130, 2,135 and 2,117 meters of altitude), P = 78.8 kPa and γ = 0.052 kPa °C-1

The mass transfer evaporation rate recommended by Penman (Dunne and Leopold, 1978) in cm/day is given by

Ea = (0.013 + 0.00016u)*((1-RH) e_{sa})

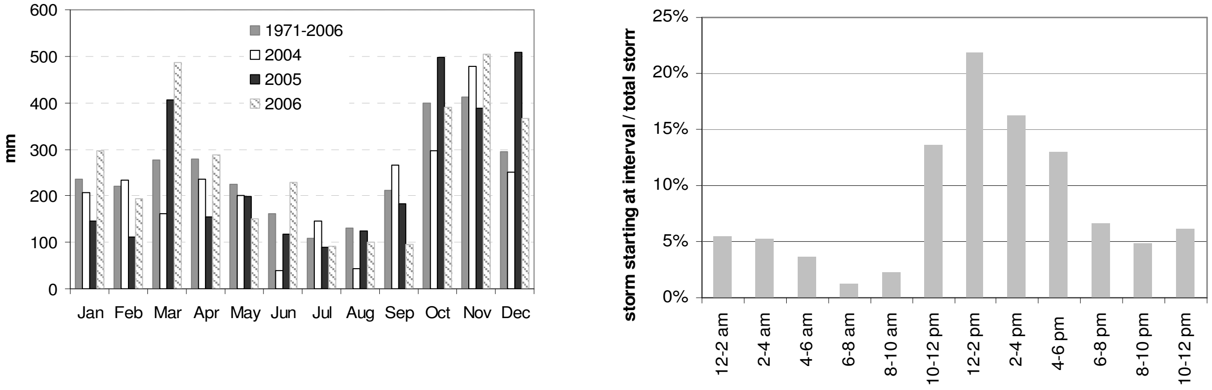
where u is the average daily wind-run in km/day, RH is the relative humidity as a decimal fraction, and e_{sa} is the saturation vapor pressure for a given T measured at 2 m above the land surface. The coefficients (0.013 and 0.00016) define an empirical relationship for the mass transfer evaporative losses over well-watered alfalfa, 30–50 cm tall (Lott and Hunt, 2001). The coefficients are adjusted for other vegetative surfaces.

PET is calculated using daily data and added up for each needed period.

Appendix 3. Precipitation characteristics in the study area

Figure 1a shows the average precipitation collected from 4 rain gauges installed for this study compared with the closest national climate station (Bremen) for a period of over 30 years (CRQ, 2008). 2004 was considered a dry year (particularly during the months of March, June and August), while 2006 was considered a wet year. No phenomena of El Niño were reported during the period of the study.

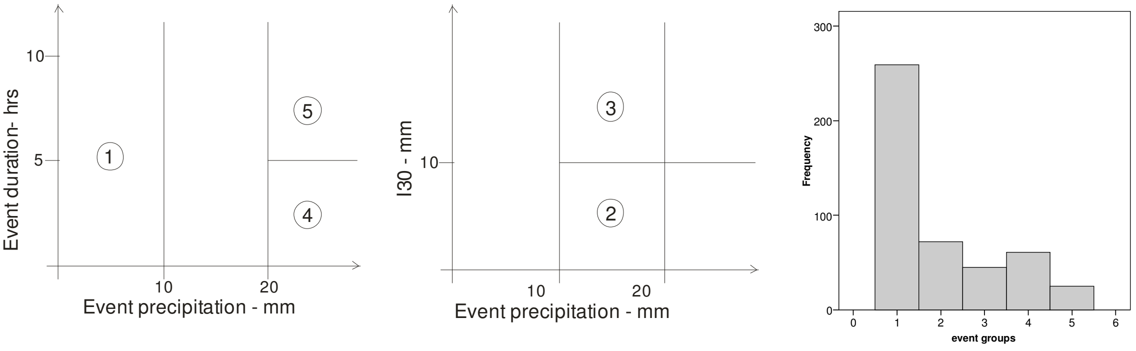
The average annual precipitation in the region since 1972 has been approximately 2,990 mm. Precipitation occurs with a unimodal diurnal peak in the afternoon (Figure 1b) explained as convective precipitation associated with solar thermal forcing favored by the entrance of low level moisture-laden winds onshore from the Caribbean and Pacific which ascend due to orographic lifting (Poveda et al., 2005).


a)

b)

Figure 1 - a) Monthly precipitation for the study area; and b) pattern of diurnal average precipitation

Five classes were identified, as shown in Figure 2a. This classification was done considering the distribution and differences found between the combinations of factors. The distribution of the resulting types is shown in Figure 2b.


a) Classification of rain events

b) Frequency distribution for BB

Figure 2 - Criteria for the classification of rainfall events and frequency distribution of event types

Figure 3 shows the typical event for each type based on the median precipitation for each 15 minute interval of each event. Event types 2 and 3 are events of the same total precipitation but type 3 is more intense. Event types 4 and 5 are also events of the same total precipitation but type 4 is shorter and therefore more intense.

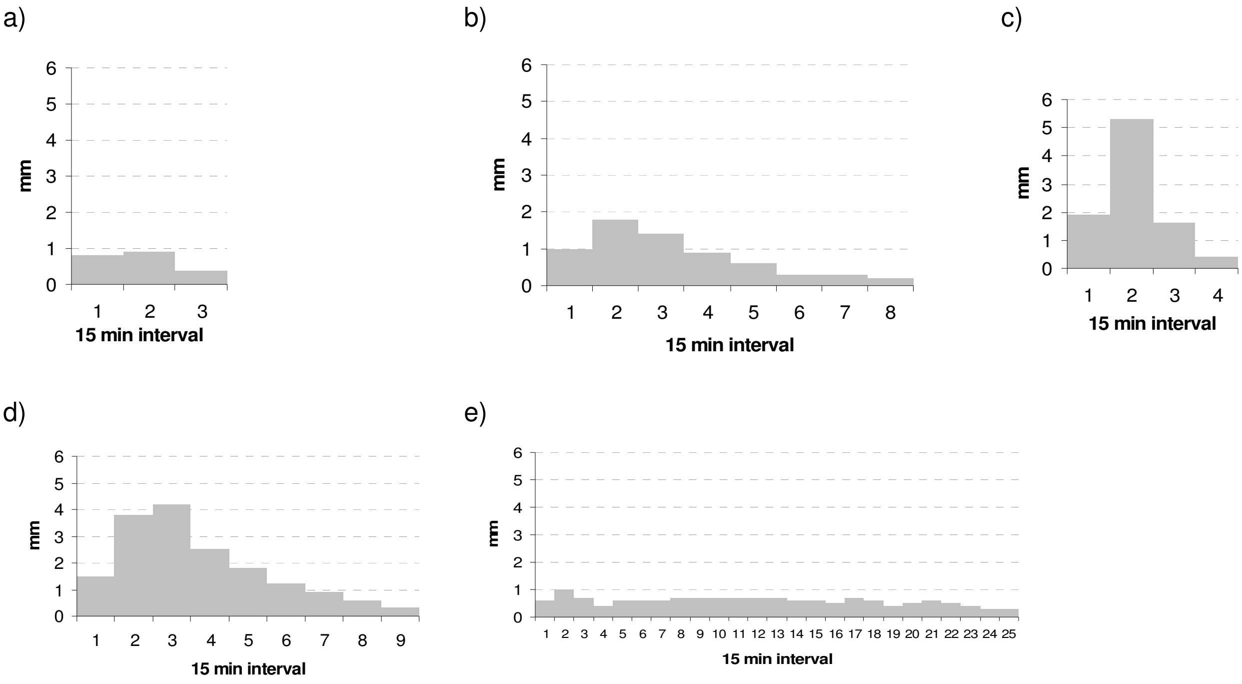


Figure 3. Typical (median) events types: a) 1; b) 2; c) 3; d) 4; and e) 5

Table 1 shows the percentage of event types in each catchment and the percentage of total precipitation for each type of event. Figure 4 shows the median event for all the events monitored.

Table 1 - Rainfall contribution of each type of event

	% of events			% of precipitation		
Event type	**B1**	**B2**	**BB**	**B1**	**B2**	**BB**
1	53%	70%	73%	20%	25%	26%
2	16%	11%	10%	16%	18%	15%
3	8%	6%	6%	9%	11%	12%
4	17%	9%	8%	38%	31%	31%
5	6%	4%	3%	17%	15%	16%

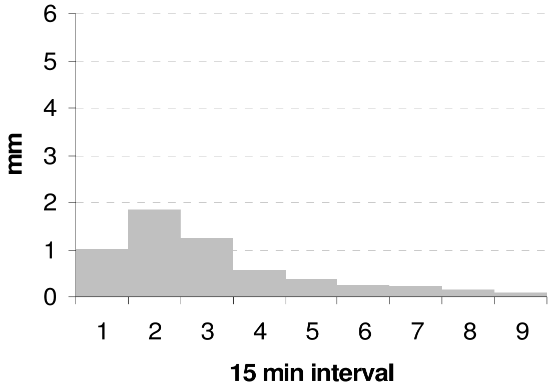


Figure 4 - Typical (median) event, all events considered

Appendix 4. Wetland inventory

Catchment	Farm	Area - m2	Name	Permanence	Water source	Fence	Surface outflow	Open water
B1	AC	229	AC38	0	R	0	0	0
B1	AC	318	AC26	0	R	0	1	0
B1	AC	612	AC29	1	R	0	1	0
B1	VR	1,008	VR4	1	R	0	0	0
B1	MC	1,072	MC2	0	R	0	1	0
B1	AC	1,308	AC27	1	R	0	1	0
B1	AC	3,384	AC28	1	R	0	1	0
B2	ER	23	ER12	0	R	0	0	0
B2	ER	26	ER3	0	R	0	0	0
B2	ER	29	ER5	0	R	0	0	0
B2	ER	38	ER11	1	R	0	1	0
B2	ER	52	ER6	0	R	0	0	0
B2	ER	53	ER2	0	R	0	0	0
B2	AC	58	AC19	1	R	1	0	0
B2	ER	59	ER4	0	R	0	0	1
B2	AC	62	AC20	1	R	1	0	0
B2	AC	326	AC22	0	R	0	1	0
B2	ER	553	ER7	1	S	0	1	1
B2	ER	471	ER9	1	R	1	1	0
B2	ER	558	ER1	0	S	0	0	0
B2	AC	632	AC39	1	R - W	1	0	1
B2	AC	698	AC25	1	R	0	0	0
B2	ER	741	ER8	0	N	1	0	0
B2	VR	777	VR2	0	R	1	1	0
B2	ER	1,045	ER10	1	N	1	1	0
B2	AC	1,563	AC21	1	R - S	0	1	1
B2	VR	1,871	VR3	0	R	1	0	0
B2	VR	2,214	VR1	1	R	0	0	0
B2	AC	14,672	AC23	1	R - S	0	1	0
BB	PR	94	PR5	1	R	0	0	0
BB	LH	113	LH8	0	R	0	0	1
BB	AC	166	AC34	1	R	0	0	0
BB	PR	192	PR3	1	R	0	0	0
BB	LH	206	LH2	1	S	1	1	1
BB	PR	259	PR2	1	R	0	0	0
BB	AC	413	AC31	1	R - W	0	0	0
BB	LH	468	LH9	1	R - W	0	0	0
BB	PR	490	PR6	1	R	0	1	0
BB	LH	501	LH5	1	R	1	0	0
BB	AC	535	AC33	1	R	0	1	0
BB	LH	717	LH6	1	R - W	0	1	0
BB	LH	722	LH7	1	R	1	1	0
BB	AC	801	AC35	1	R - W	1	1	0
BB	PR	802	PR1	1	R	0	0	0
BB	AC	894	AC32	1	R	0	1	0
BB	LH	1,598	LH1	1	R	1	1	1
BB	AC	2,618	AC30	1	R - S	0	0	0
BB	LH	2,771	LH3	1	R	1	0	0
BB	AC	4,380	AC36	1	R - S	0	1	0
BB	AC	4,896	AC18	1	R - S	0	1	1
BB	LH	8,180	LH10	1	R	0	1	0
BB	LH	6,650	LH4	1	R - W	1	1	0

Water Source:

R – Rain
S – Spring
W – Wetland

Farm:

AC – Aguas Claras
VR – Veracruz
LH – La Herradura
PR – Providencia
EL – El Roble
MC – La Macenia

Wetlands highlighted in gray were chosen for the detailed monitoring program.

Appendix 5. Summary of plan inventory

Wetland	Number of quadrants	Number of plants found	Dominant plants	% cove-rage
B1	15	23	Axonopus compressus (Sw.) P. Beauv.	30
			Juncus effusus L.	25
			Eleocharis maculosa (Vahl) Roem. & Schult.	12
			Hyptis atrorubens Poit.	6
			Hydrocotyle sp.	5
				78
B2	12	30	Juncus effusus L.	53
			Axonopus compressus (Sw.) P. Beauv.	8
			Critonia sp.	5
			Axonopus scoparius (Flugge) Duhlm.	5
			Elleanthus elegans R et Sch	4
				75
BB	37	53	Eleocharis maculosa (Vahl) Roem. & Schult.	21
			Hydrocotyle sp.	13
			Axonopus compressus (Sw.) P. Beauv.	9
			Selaginella sp.	4
			Brachiaria decumbens Stapf.	4
				51

Appendix 6. Event precipitation and wetland discharge

Table 1 - Flow and water storage for: a) B1; b) B2; and c) BB.

a) B1

Event type	season	N	median event precipitation (mm)	median wetland discharge / precipitation	change in volume (mm)
1	dry	24	4.2	20%	18.1
	wet	77	4.6	15%	4.8
2	dry	6	12.2	15%	34.0
	wet	22	13.1	23%	9.0
3	dry	5	16.1	9%	60.4
	wet	7	15.1	24%	14.1
4	dry	11	25.5	63%	62.9
	wet	25	28.2	41%	29.9
5	dry	1	26.1	34%	23.6
	wet	9	32.1	35%	14.4
Average				28%	

b) B2

Event type	season	N	median event precipitation (mm)	median wetland discharge / precipitation	change in volume (mm)
1	dry	44	4.0	18%	9.4
	wet	169	4.8	27%	5.6
2	dry	14	13.6	18%	48.5
	wet	55	13.0	23%	19.2
3	dry	5	13.9	11%	78.1
	wet	30	16.4	16%	41.8
4	dry	16	29.9	13%	183.7
	wet	38	27.6	19%	80.5
5	dry	3	28.5	16%	157.0
	wet	19	31.2	23%	43.9
Average				18%	

c) BB

Event type	season	N	median event precipitation (mm)	median wetland discharge / precipitation	change in volume (mm)
1	dry	61	4.8	1%	6.9
	wet	159	4.6	5%	4.0
2	dry	16	12.4	3%	14.4
	wet	49	12.4	10%	9.0
3	dry	11	15.7	4%	20.5
	wet	30	15.6	9%	16.0
4	dry	13	31.5	12%	31.5
	wet	45	26.4	16%	21.7
5	dry	2	30.4	18%	20.6
	wet	22	32.0	18%	17.9
Average				9%	

Appendix 7. Time lags for wetlands and streams

During intense events (types 3 and 4) the time lag to peak in flow for BB is only 1.5 hours after the beginning of the event in the wet season and 2.5 and 1.8 hours for events type 3 and 4 respectively in the dry season. In most cases the time lag to peak in flow is longer in the dry season than in the wet season, the exception being type 1 events for all wetlands and for events of type 2, 3 and 4 in B2. This is explained by the smaller wetland-to-catchment ratio for B2 since after the rain stops, the water continues to flow into the wetland from the contributing area. B1 wetland volume reaches its peak earlier in the wet season than in the dry season, since its water storage capacity is low and its fluctuation in water level is small. For B2 and BB the time lag to peak in volume depends greatly on the time of the storm in the season, since the wetland water storage capacity is dependent on antecedent moisture conditions.

For events type 5 (long but not intense events), all the wetlands have longer lag to peaks in flow than lag to peaks in volume. Although events type 5 are between 3% and 6% of all the events, the precipitation of these events accounts for between 15% and 17% of the total precipitation.

There is an important difference in flow and water storage between the dry and wet seasons. In the dry season the wetlands are not at full storage capacity. For wetlands B2 and BB the discharge since the beginning of the rain event until two hours after it stops raining, is greater in the wet seasons in comparison with the discharge in the dry seasons, which indicates the water holding capacity of the wetlands and their contributing areas. This is not the case for type 1 events (very short and small) and type 4 events (short and intense) in wetland B1. For type 1 events this might be attributable to a greater variation in event duration and intensity and for type 4 events it is explained by the limited capacity of B1 wetland to store rain that falls as a sudden large storm event.

Table 1 - Time lags to peak in volume (tlpv) and peak in flow (tlpf) for each wetland and event type in minutes for: a) wet season storms; and b) dry season storms. The small numbers in *italics* in the table indicate the number of events monitored for each parameter.

a) wet season

lags	**tlpv**	**tlpf**	**tlpv**	**tlpf**	**tlpv**	**tlpf**
Event type	**WB1**		**WB2**		**WBB**	
1	*n=161* 60	*n=30* 68	*n=182* 90	*n=169* 60	*n=153* 60	*n=152* 165
2	*n=58* 75	*n=19* 75	*n=57* 120	*n=55* 120	*n=43* 75	*n=51* 150
3	*n=23* 45	*n=6* 45	*n=34* 60	*n=32* 60	*n=24* 45	*n=30* 90
4	*n=55* 60	*n=25* 60	*n=40* 75	*n=37* 75	*n=29* 60	*n=44* 90
5	*n=25* 150	*n=8* 202	*n=20* 218	*n=19* 225	*n=21* 165	*n=22* 225

b) dry season

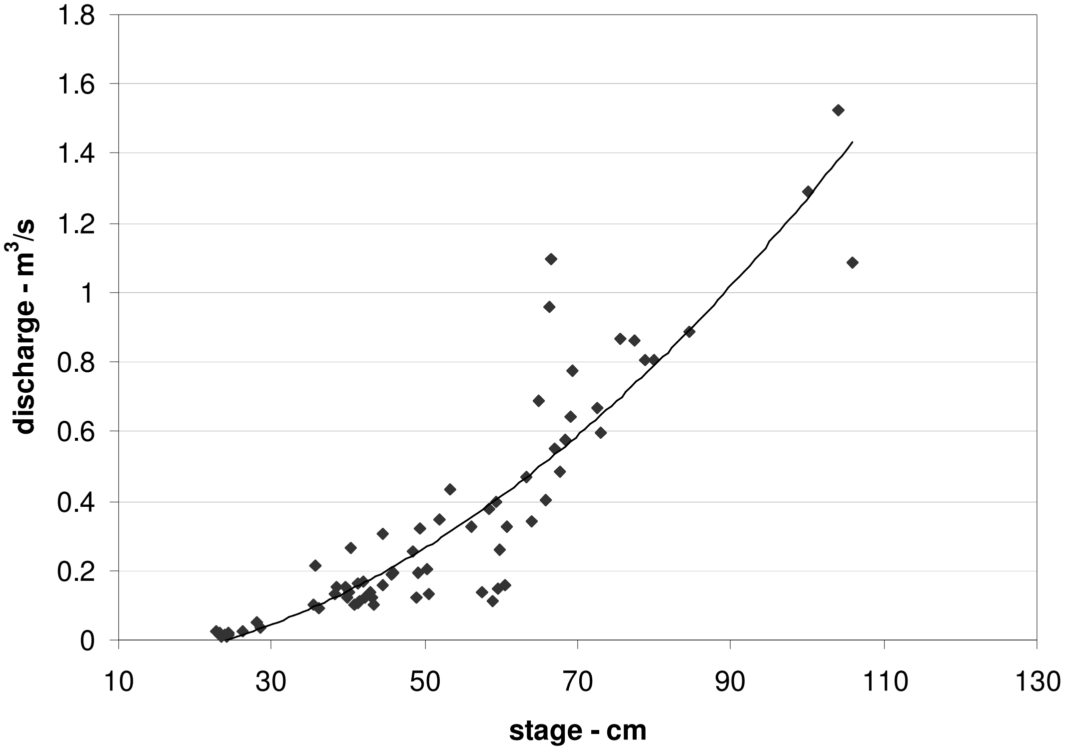
Lags	**tlpv**	**tlpf**	**tlpv**	**tlpf**	**tlpv**	**tlpf**
Event type	**WB1**		**WB2**		**WBB**	
1	*n=70* 75	*n=21* 60	*n=70* 90	*n=44* 60	*n=63* 60	*n=60* 98
2	*n=13* 90	*n=5* 90	*n=21* 150	*n=14* 105	*n=15* 105	*n=15* 180
3	*n=12* 60	*n=5* 60	*n=8* 60	*n=5* 60	*n=11* 30	*n=10* 150
4	*n=19* 75	*n=11* 120	*n=18* 67.5	*n=16* 60	*n=10* 97.5	*n=12* 112
5	*n=3* 345	*n=1* 390	*n=4* 270	*n=3* 315	*n=2* 210	*n=2* 308

Table 2 - Time lags to peak in flow (tlpf) for each stream and event type in minutes

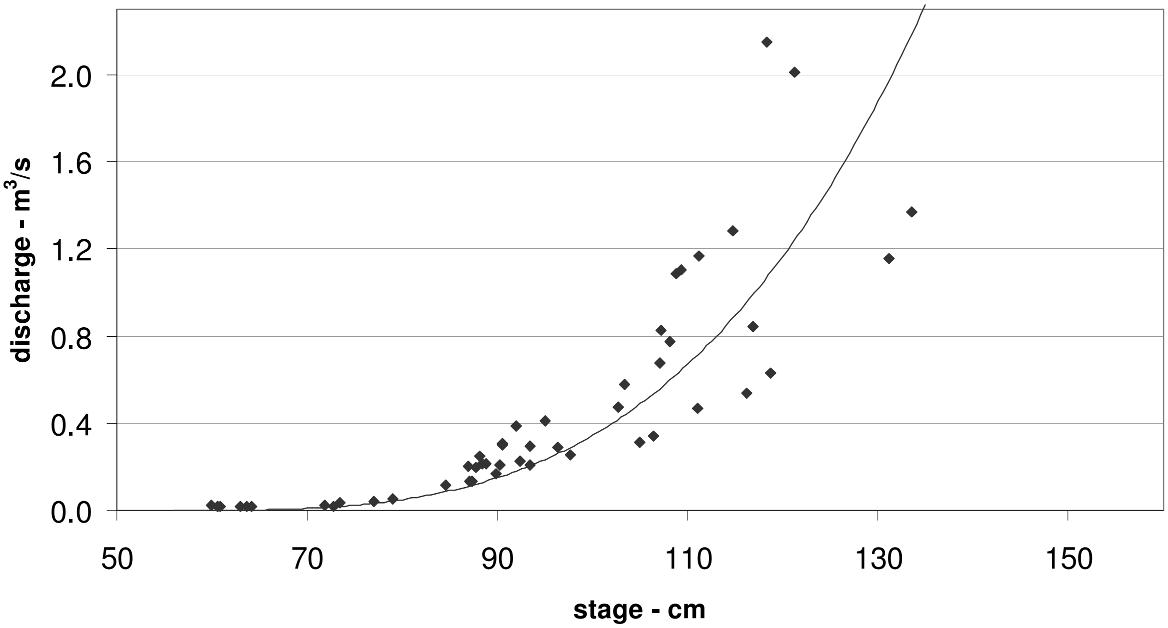
	Wet season tlpf			**Dry season tlpf**		
Event group	**B1**	**B2**	**BB**	**B1**	**B2**	**BB**
1	*n=155* 105	*n=170* 105	*n=171* 120	*n=65* 120	*n=55* 135	*n=66* 90
2	*n=58* 135	*n=56* 135	*n=52* 135	*n=13* 150	*n=15* 165	*n=15* 165
3	*n=22* 75	*n=24* 75	*n=31* 75	*n=11* 150	*n=7* 135	*n=11* 75
4	*n=51* 75	*n=34* 75	*n=46* 67.5	*n=17* 135	*n=12* 75	*n=12* 105
5	*n=23* 180	*n=19* 225	*n=21* 225	*n=3* 240	*n=1* 300	*n=2* 285
Averages	109	112	117	132	134	104

Appendix 8. Stage-discharge relationships

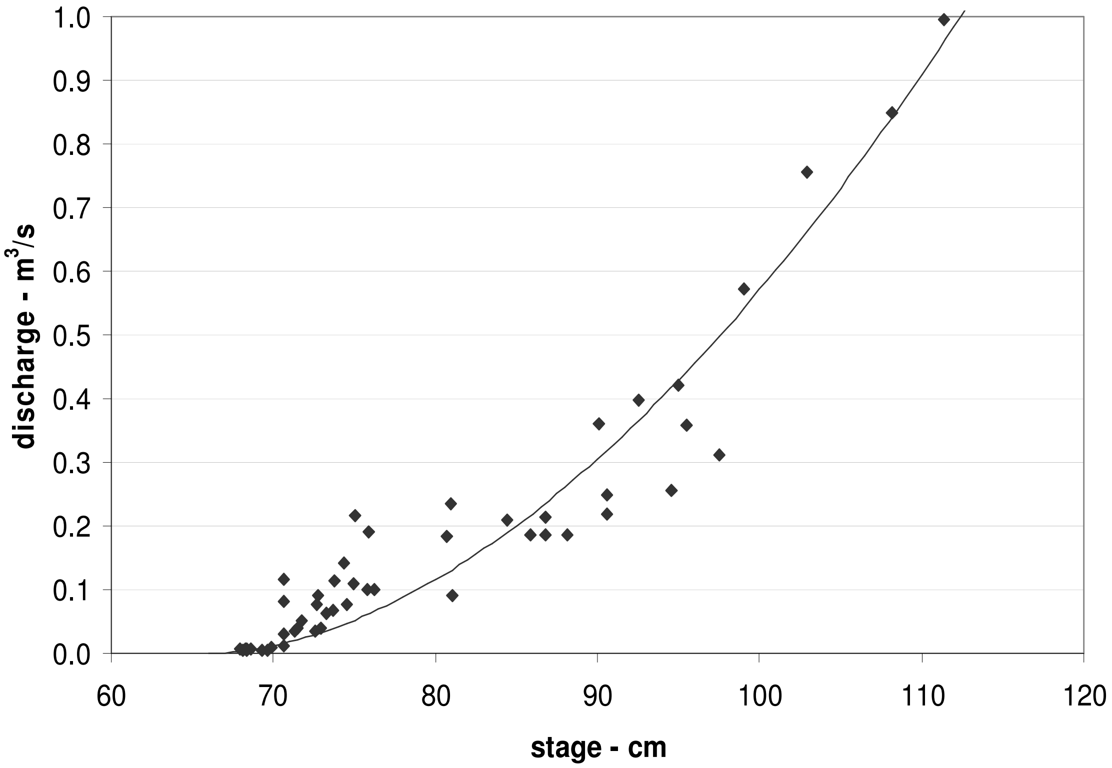
a) stream B1



b) stream B2



c) stream BB



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
discharge - m^3/s
60
70
80
90
100
110
120
stage - cm

Appendix 9. Discharge coefficients for each catchment by event type and season

B1	**Event type**	**Season**	**n**	**median precip. (mm)**	**median stream discharge (mm)**
	1	dry	68	4.2	0.6
		wet	161	4.6	1.4
	2	dry	13	12.2	0.9
		wet	58	13.1	2.8
	3	dry	11	16.1	0.9
		wet	22	15.1	2.3
	4	dry	17	25.5	1.8
		wet	51	28.2	4.7
	5	dry	3	26.0	3.2
		wet	23	32.1	10.5

B2	**Event type**	**Season**	**n**	**median precip. (mm)**	**median stream discharge (mm)**
	1	dry	56	4.0	0.6
		wet	178	4.8	1.4
	2	dry	15	13.6	1.3
		wet	57	12.9	4.1
	3	dry	7	13.8	1.1
		wet	28	16.4	2.9
	4	dry	12	29.9	3.9
		wet	37	27.8	7.5
	5	dry	1	28.5	
		wet	18	31.2	11.7

BB	**Event type**	**Season**	**n**	**median precip. (mm)**	**median stream discharge (mm)**
	1	dry	70	4.8	0.4
		wet	175	4.6	1.0
	2	dry	15	12.4	0.8
		wet	52	12.4	2.6
	3	dry	11	15.7	1.3
		wet	31	15.6	3.6
	4	dry	12	31.5	7.2
		wet	46	27.2	7.7
	5	dry	2	30.4	6.5
		wet	21	32.0	12.5

Appendix 10. Hydrograph comparison for streams and wetlands by event type and season

When an event type 4 occurs in the dry season, the discharge from B1 wetland is significantly higher than the discharge from the other two wetlands which remain very low. The discharges from the streams are of similar magnitude as seen in Figure 1. What this shows is that B2 and BB wetlands are re-filled before they initiate their water discharge and that the low water storage capacity of B1 wetland does not hold any water in the dry season.

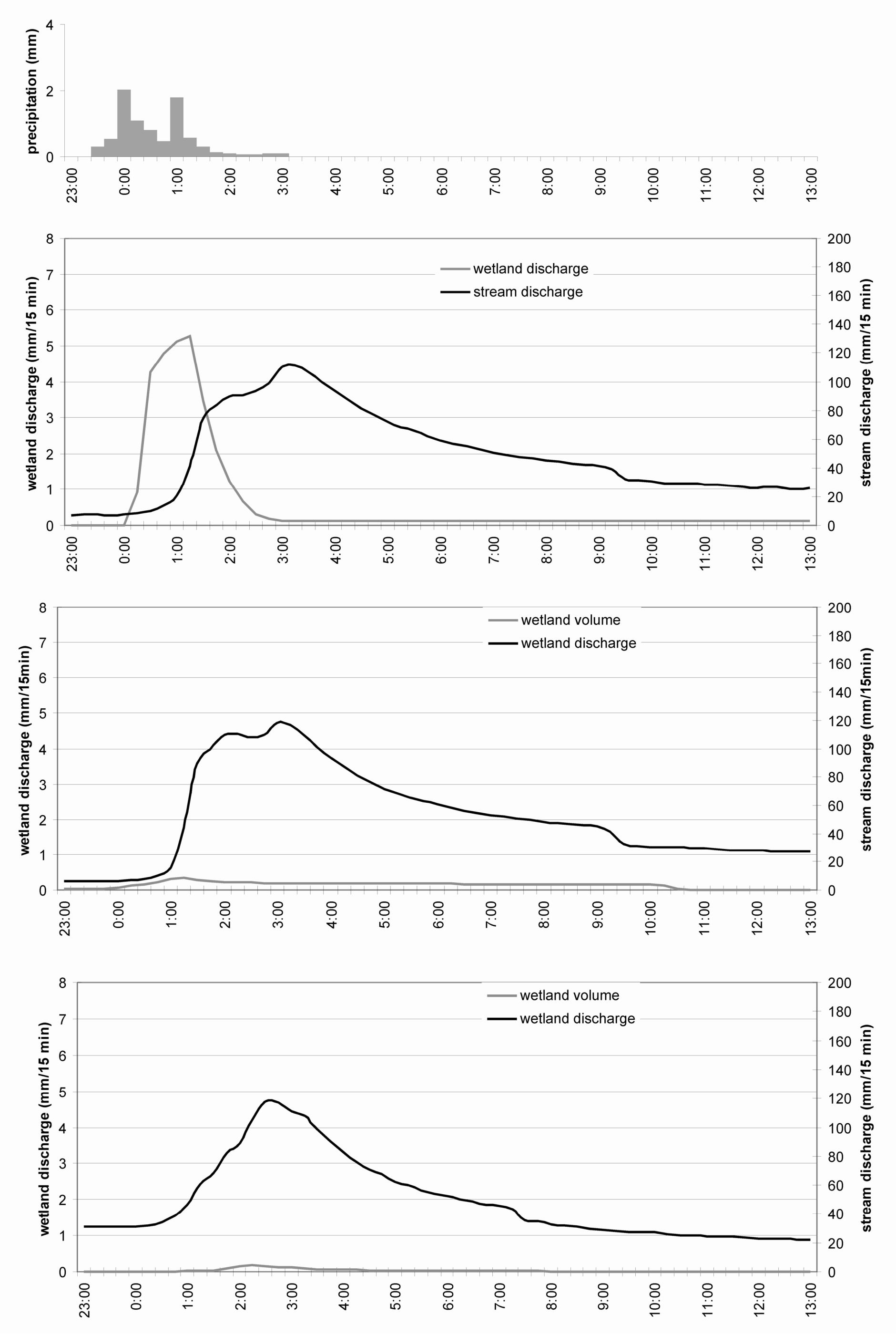


Figure 1. Event Type 4 in dry season – Oct. 13th, 2006 in: a) B1; b) B2; and c) BB.

Large and long events (Type 5) occur mostly in the wet season and produce a similar response in the wetlands to the effect of events Type 4; B1 wetland produces a larger discharge than the other two wetlands, illustrating the small water holding capacity of B1. At the catchment scale however, B1 catchment shows a smaller peak discharge and a more gradual decrease in discharge than the other two catchments. This could be related to the larger forest area combined with a large but low intensity rain pattern. See Figure 2.

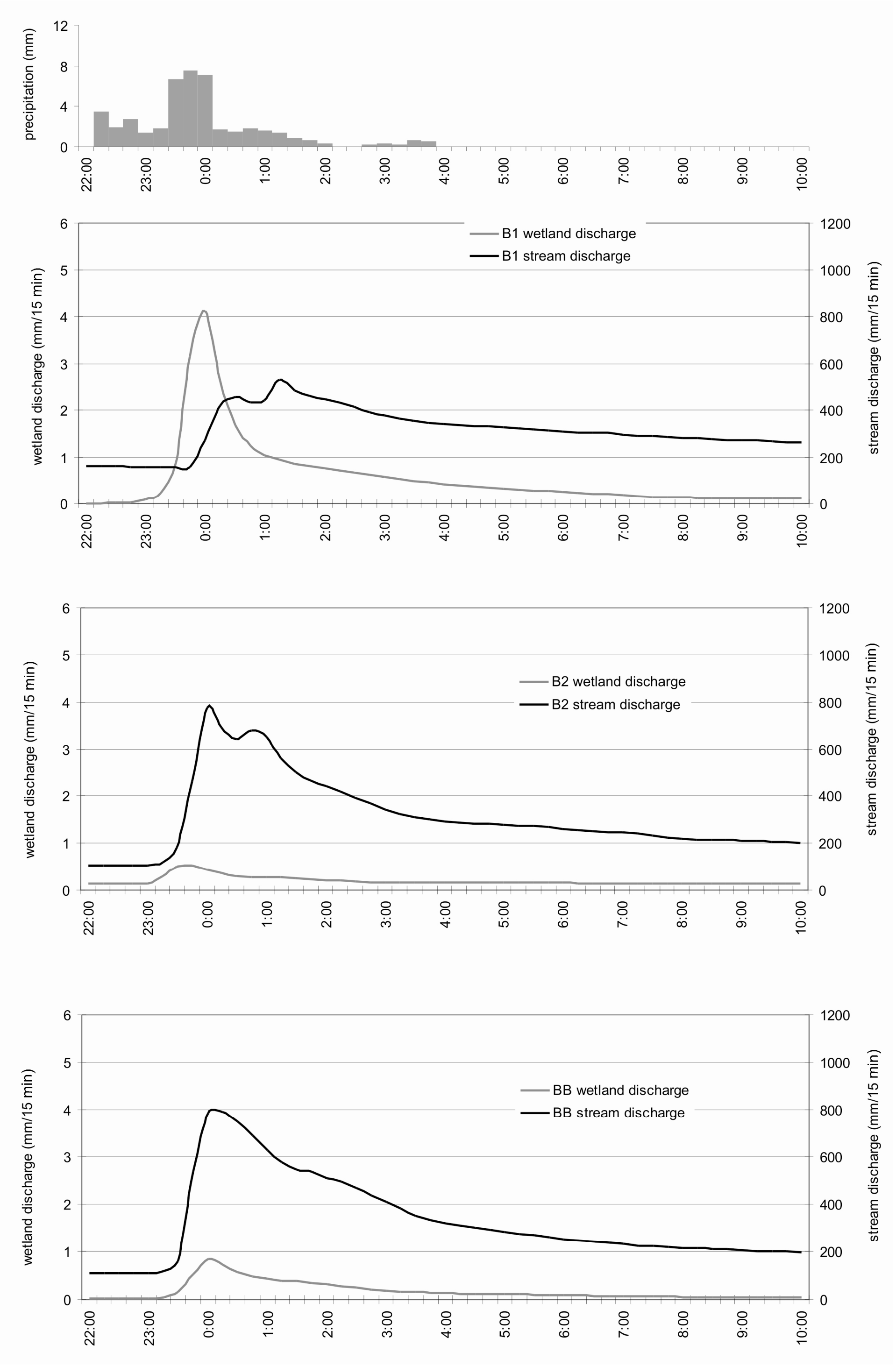


Figure 2. Event Type 5 in wet season – Dec. 8th, 2006 in: B1; B2; and BB.

Appendix 11. δ ^{18}O in precipitation and streams for five events sampled

	Event	2	3	5	6	7
δ 18O (‰)	Date	14-Nov-06	21-Nov-06	7-Apr-07	18-Apr-07	25-Apr-07
Precipitation	Min	-24.6	-20.1	-19.4	-12.0	-21.7
	Max	-16.5	-17.8	-16.1	-10.1	-21.4
B1S	Min	-13.7	-13.0	-15.0	-11.6	-17.4
	Max	-11.3	-11.6	-11.3	-10.8	-12.0
B2S	Min	-13.4	-12.2	-14.2	-11.4	-15.1
	Max	-11.3	-11.5	-11.3	-10.8	-11.9
BBS	Min	-12.8	-15.0	-13.0	-12.1	-18.1
	Max	-11.9	-13.3	-11.7	-10.1	-11.8
B1W	Min	-16.0	-14.6	-17.6	-11.9	-19.8
	Max	-11.8	-12.6	-12.1	-11.2	-12.6
B2W	Min	-11.3	-12.1	-15.5	-11.3	-16.4
	Max	-11.0	-11.2	-11.1	-10.8	-11.9
BBW	Min	-13.6	-16.3	-13.1	-12.0	-18.2
	Max	-12.8	-14.2	-11.9	-11.4	-12.4

(S = stream outflow; W = wetland outflow)