Tradeoffs between hydropower generation and environmental impacts in the Alto Magdalena River basin

A thesis submitted by

Susan Bresney

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Adviser: James Limbrunner

Abstract

A systems approach is used to present the tradeoffs between power generating capacity and impacts to streamflow and river connectivity among different scenarios of hydropower development in the Alto Magdalena River basin, Colombia. This analysis defines a non-inferior set of 15 development scenarios which minimize connectivity loss while maximizing generating capacity. Streamflow impacts were assessed using WEAP, and results show that while building reservoirs upstream of existing dams best maintains connectivity, this causes greater local streamflow impacts than downstream development. Upstream consequences may affect a smaller fish population than downstream, but this population is largely endemic. Impacts of upstream development on downstream flows are minor due to the influence of existing dams between the two reaches. This work provides information to support the decision making process in hydropower development and suggests the need for cooperation among local and national entities as well as for a larger set of performance measures.

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Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

Colombia, located in northwest South America, is a country made up of a variety of ecosystems and is rich in natural resources including oil, minerals, biodiversity and fresh water (Lavaux, 2006). The Andes Mountains, which cover the northeast region of the country, are made up of three ranges extending parallel from southwest to northeast: the Cordillera Occidental, Cordillera Central and Cordillera Oriental. The highest peak in Colombia, Nevado del Huila, lies in the Cordillera Central at 5,780 meters above sea level (Parques Naturales, 2015). The Magdalena River, the longest river in Colombia, at over 1,500 kilometers, flows between the Cordillera Central and Oriental, from the peaks and cloud forests of the Andes through multiple biodiverse ecosystems, one of which is the Mompos Depression, one of the largest wetlands in the world, before flowing into the Caribbean Sea (Angarita et al., 2015, **Figure 1-1**). The entire Magdalena River basin covers 24% of Colombia's area, 271,249 square kilometers, including much of the Andean Region. At the mouth of the river near Baranquilla, the multiannual average discharge (based on data from 1975-1995) of the Magdalena River is 7,200 cubic meters per second (Restrepo and Kjerfve, 2000).

Not only the largest, the Magdalena River is also the most important river in Colombia. Thanks to the basin's relief and significant flow rate, there is great hydropower potential, some of which has already been exploited to fill a significant portion of Colombia's energy needs. Currently, between 60% and 82% of Colombia's overall energy needs are generated by hydropower (Ospina-Noreña, 2009; International Energy Agency [IEA], 2014; Opperman et al., 2015)

(9,185 MW by large hydropower and 591 MW by hydropower with project capacities of less than 20 MW (Morales et al., 2015)) and 60% (IEA, 2014) to 84% (Jiménez-Segura et al., 2014) of that is generated in the Magdalena River basin. The river also provides drinking water for most of the country's population and supports 75% of the country's agriculture production (The Nature Conservancy [TNC], 2015b). The basin is home to 80% of the country's population, and to 213 fish species, of which, 50% are endemic (Jiménez-Segura et al., 2014) and 40 are listed as threatened (IUCN, 2013), making it an integral resource for fishing and important for conservation. The majority, 86% of the Colombian GDP is produced within the basin (TNC, 2015b), and the river is an integral part of Colombian culture in general (Caycedo, 2015). The Magdalena River is the largest river discharging into the Caribbean Ocean, transporting more sediment than any other river flowing into the Caribbean Ocean by at least an order of magnitude (Milliman & Farnsworth, 2013). The Magdalena River even transports some of the highest volumes of sediment compared to other South American rivers, including those with significantly larger discharge and drainage areas such as the Amazon, Orinoco and Paraná Rivers (Restrepo and Kjerfve, 2000; Angarita et al., 2015). This immense capacity to transport sediment, and the variation in flows that support such transport makes the Magdalena River essential to maintaining the health of the river's ecosystem (Angarita et al., 2015) as well as the ocean's (Restrepo et al., 2006).

Although the basin already supplies extensive hydropower, it is estimated that the country has a total hydropower potential of 93,085 MW, ten times more than existing installed capacity (CORPOEMA, 2010), with 25,000 MW of this estimated to be in hydropower projects with capacities less than 20 MW (Morales et al., 2015). Of the 10% of total potential that has been exploited, 9.86% includes projects greater than 20 MW in size, and 0.57% includes projects less than 20 MW (CORPOEMA, 2010). The Magdalena River basin alone is estimated to hold nearly 40% of the total potential (Morales et al., 2015).

The Colombian government, with the support of HydroChina and Power China, has established a plan to act on this potential by developing significantly more hydropower within the Magdalena River basin to meet increasing demand in Colombia as well to be sold internationally to Ecuador and Venezuela ("The Republic", 2013). This is just one proposed plan of many which contribute towards the country's energy generation expansion plan (UPME, 2013). The expansion plan proposes to increase the country's energy generation capacity by 7,914 MW (UPME, 2013). Colombia plans to account for more than 77% of this increase in generation by building new hydroelectric power plants summing 6,088 MW (UPME, 2013). While hydropower can provide significant energy with potentially low carbon emissions, it does not come without environmental, social, and economic impacts which vary by project type, size and location. This study aims to assess the tradeoffs between the increased power generation capacity and resulting impacts to stream flows and river connectivity from proposed small and large hydropower projects in one portion of the Magdalena River basin and to consider the influence of current government practices on future hydropower development and its impacts.

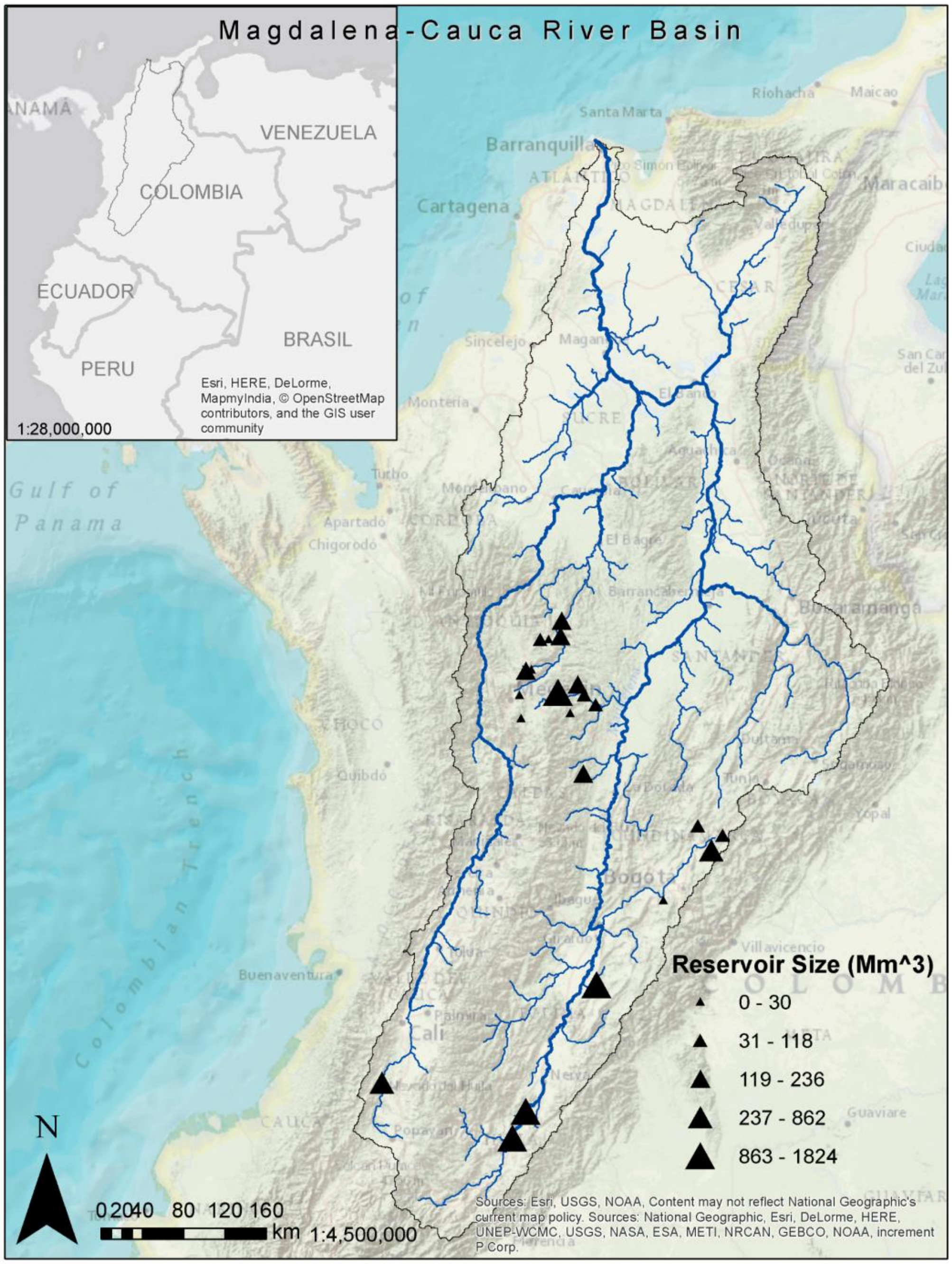

Figure 1-1. *Map of the Magdalena River basin and its location within Colombia, as well as existing dams in the basin (FAO, 2016)*

Chapter 2 Review of Colombian water governance

Law 99, passed in 1993 was a major piece of Colombian legislature that called for a complete overhaul of the Colombian environmental governance system (Blackman et al., 2012). The law called for decentralizing the environmental regulating process, requiring nongovernmental entities to be involved in the decision making process, and allowing jurisdiction boundaries to be controlled by watershed delineation rather than political boundaries (MacDonnell and Grigg, 2007, Blackman et al., 2012).

2.1 The National Environmental System

Law 99 established a new management system and reporting structure: the National Environmental System (Sistema Nacional Ambiental (SINA)) and entities for the management and designation of specific responsibilities (Blackman et al., 2012). The new Ministry of the Environment and Sustainable Development (Ministerio de Ambiente y Desarrollo Sostenible (Ministry)), was created as the directing agency of the SINA, and is responsible for setting national environmental regulations including pollution standards and fine structure, administration of national protected areas (Blanco, 2008), and methodologies for granting or denying environmental licenses (Decreto 2041, 2014). Specifically for water resources management, the national government is supported in developing regulations and standards by the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), a national research institution in charge of meteorology and environmental studies also created by Law 99 of 1993 (Blanco, 2008), the

Department of Integrated Water Resources Management (Dirección de Gestión Integral del Recurso Hídrico, Ministerio, 2016) and the National Authority of Environmental Licensing (Autoridad Nacional De Licencias Ambientales (ANLA), Decreto 2041, 2014). Implementation of the environmental and water resource policies set by the Ministry is mainly conducted at the regional level, by the Regional Autonomous Corporations (Corporaciones Autónomas Regionales (CARs)), who are responsible for managing a watershed or subwatershed (MacDonnel and Grigg, 2007). However, the CARs do not have complete authority over large projects even if they fall within their jurisdictional area. Large projects are licensed at the national level by the ANLA (Decreto 2041, 2014).

The autonomy of the CARs manifests itself in different ways for different areas. First, the CARs each have a regional board, made up of representatives from regional departments, municipalities, NGOs, business and ethnic groups as well as national representatives from the Ministry and possibly the President. The majority of the CAR's budget is generated by regional property taxes and environmental taxes within their jurisdiction, with additional funds supplied by the national government. Environmental taxes are jurisdiction based, including revenues from water use licenses, discharge permits, and royalties from hydropower plants within their jurisdiction. Using local funds allows the CARs to allocate resources to projects that are most regionally important, but this design also significantly reduces the availability of funds, and therefore the capacity of CARs to carry out their responsibilities in less developed areas. (Blanco, 2008)

2.2 Environmental Licensing and Hydropower regulations

The main method of exercising environmental protection and regulation in Colombia is through the system of environmental licensing. A license is required for “the execution of a project, work or activity… which may cause severe deterioration of renewable natural resources or the environment or introduce considerable or notorious modifications to the landscape” (translated from Decreto 2041, 2014). One license is required per project and includes consideration for any implications to the environment or use of natural resources during construction and operation of the project. For hydropower projects, a license will include both requirements for environmental protection and mitigation during construction as well as a water use license for operation of the dam or diversion. (Decreto 2041, 2014)

There are four entities which can grant or deny licenses, and this study focuses on the two entities which are most commonly responsible. At the national level, the ANLA grants and denies licenses for large projects and at the regional level, the CARs do so for smaller projects. The CARs may also delegate this responsibility to local authorities. In the case of hydropower, the ANLA is responsible for projects with capacities greater than 100 megawatts or with reservoirs larger than 200 million cubic meters and the CARs are responsible for all smaller projects. Throughout this study, “large hydropower” is used to refer to those that the ANLA licenses. What is considered “small” hydropower varies from country to country, ranging from <1.5 MW to <100 MW (Morales, 2015) but in this study, small hydropower, (Pequeñas Centrales Hidroeléctricas (PCH)), unless otherwise stated, is used to refer to those projects that the CARs have jurisdiction over. (Decreto 2041, 2014)

Prior to 1994, the majority of the electricity sector in Colombia was owned and operated by the government (Blackman et al., 2012). The sector was restructured allowing for private investment (Uribe and Medina, 2004), as a reaction to severe, drought-induced electricity shortages in 1992 and 1993 (Blackman et al., 2012). Currently, private companies can apply for an environmental license to construct and operate new electricity generating plants from the corresponding authority (either the ANLA or the CAR with jurisdiction over the region where the project is located) (Decreto 2041, 2014). In order to apply for a license from either entity, applicants are required to conduct an Environmental Impact Assessment as well as plans for mitigation or alternative plans for development to minimize these impacts (MacDonell and Grigg, 2007, Decreto 2041, 2014). In conducting environmental impact studies, the applicant must follow the terms of reference for conducting studies provided by the General Methodology for the Submission Environmental Studies (Metodología General para la Presentación de Estudios Ambientales), which is developed and updated by the Ministry and the ANLA (Decreto 2041, 2014). If the applicant is applying for a license from the ANLA, this information must also be supplied to the corresponding CAR (Decreto 2041, 2014). Additionally, the applicant must share development plans and impact assessments with the public, and in some cases, consult with indigenous populations (Decreto 2041, 2014).

In assessing the impacts presented in the studies, both the ANLA and the CARs are required to follow the Evaluation Manual for Project Environmental Studies (Manual de Evaluación de Estudios Ambientales de Proyectos), also developed and updated by the Ministry and the ANLA (Decreto 2041, 2014). This may include a visit to the site of the proposed project as well as considering economic and social impacts, availability of the resource and the proposed water use in relation to other users (Decreto 2041, 2014). Under law, utilization of water by any individual user must not result in injury to the general interest of the community or the rights of other users (MacDonnell and Grigg, 2007). Although both entities follow the same procedures in assessing impacts and therefore granting or denying licenses, the CARs do not participate in developing the procedures or standards for which these impacts are measured and assessed. Additionally, although the CARs may be consulted in the licensing process by the ANLA, the period of time in which the CARs can provide feedback on assessments to the ANLA is limited (Decreto 2041, 2014). Despite the participatory structure of the decision making process, and the inclusion of non-government entities and individuals on the boards of the CARs, the lack of effective methods of communication between the two levels of government, and the limited resources available to the CARs compared to the national government may mean that participation and cooperation is not always successful in practice.

2.3 Additional Responsibilities of the CARS

In addition to licensing, the CARs protect the environment within their jurisdiction by developing various watershed management plans, known as ordering plans, and reviewing the environmental aspects of local Territorial Ordering Plans (POT) set out by the municipalities (Blanco, 2008). These plans include limitations of areas to be used for urban expansion and development, and impose restrictions on areas intended for environmental, cultural or historic protection (Blanco, 2008). CARs can also establish reserves of environmental resources and once a reserve is established, no licenses may be issued for the reserved resource (MacDonell and Grigg, 2007).

Chapter 3 Alto Magdalena basin and its development plans

The Magdalena River basin is divided into multiple CARs. This analysis focuses on the area of the basin which is managed by the CAR called the Regional Autonomous Corporation of the Alto Magdalena (la Corporación Autónoma Regional del Alto Magdalena (CAM)). This portion of the basin, the Alto Magdalena basin, encompasses the headwaters of the river and falls within the department of Huila (**Figure 3-1**).

Currently, there are two large dams on the main stem of the Magdalena River, which are located within the jurisdiction of the CAM (**Figure 3-1**), but are licensed by the national government. Betania has been operating since 1988 with its main priority as hydropower generation. Construction of El Quimbo commenced in 2012 and operations began in December 2015. Initially, the operations of El Quimbo led to a significant decline in water quality due to the decomposition of residual tree debris that was not removed before the reservoir was filled (CAM WEAP team meeting, January 8, 2016; “El Quimbo”, 2016). Low levels of dissolved oxygen and other issues in water released from El Quimbo killed fish in the tilapia farms in the Betania reservoir downstream, affecting not just the fish but the livelihood of those who depend on the fish farms (CAM WEAP team meeting, January 8, 2016). The issues with El Quimbo have led to increased resistance to large dams in the area (see for example “El Quimbo”, 2016). There are also two existing PCHs, which have been in operation for approximately 40 years (L.Obregon Salazar, Civil Engineer, CAM, personal communication, January 21, 2016). These projects are not connected to the grid and only supply power locally.

Many plans for new hydropower projects have been proposed throughout the Magdalena River basin. One major plan proposed by the national government includes construction of 17 large dams on the main stem of the Magdalena River ("The Republic", 2013). These large projects would be licensed by the ANLA, and are not just proposed to meet the energy needs of Colombia, but also to export energy to Ecuador and Venezuela ("The Republic", 2013). Of the 17 proposed large mainstem projects, eight fall within the study area, four are proposed for sites upstream of Betania and El Quimbo, and four downstream (**Table 3-1**, **Figure 3-1**). These projects have significant storage and generate power by releasing water from the reservoir through turbines (**Figure 3-2**a). Throughout this analysis, "upstream" refers to the area in the Alto Magdalena basin upstream of El Quimbo, and "downstream refers to the area downstream of Betania (**Figure 3-1**).

In addition to, and separate from plans for the large projects, and separate from each other, the CAM has received license solicitations for eight PCHs to be operated as run of river hydropower plants within the Alto Magdalena River basin (CAM, n.d.). Five of these projects are included in this analysis (**Table 3-1**, **Figure 3-1**). PCHs are operated without any or with little storage, and generate power by diverting water from the river and using the natural elevation change of the landscape. The diverted water is routed through a turbine and discharged back to the river downstream (**Figure 3-2**b). The projects for which the CAM has received solicitations have one of two types of diversions, one which diverts water directly from the river to the intake, and the other using a weir to pool water at the intake (as shown in **Figure 3-2**b; O. Moncayo Calderón, Agricultural Engineer, CAM, personal communication, January 20, 2016). Which intake structure is included in the proposed plans is determined based on how low the low flows are in the river and which intake structure allows for more efficient water use during drier periods. The design of the intake structure is considered by the CAM when they assess environmental impacts of the projects during the licensing process (O. Moncayo Calderón, Agricultural Engineer, CAM, personal communication, January 20, 2016).

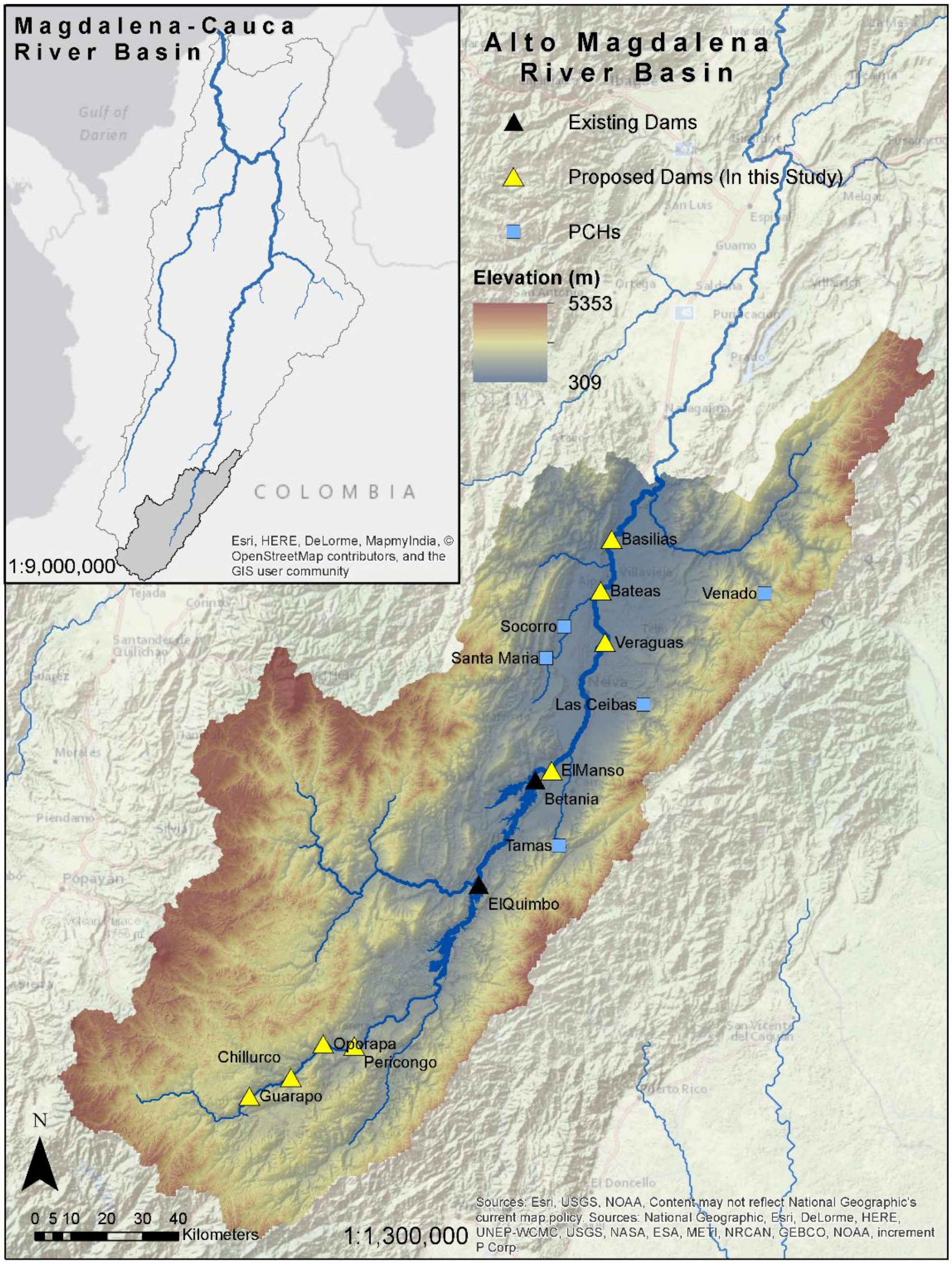

Figure 3-1. *Map of the Alto Magdalena River basin and the location of proposed projects included in this study.*

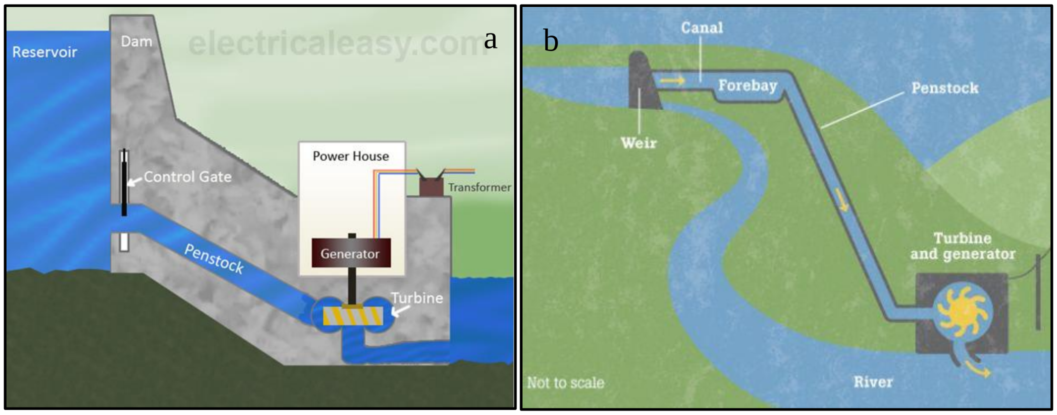

Figure 3-2. *Schematic of large hydropower project with a reservoir (a) (Daware, n.d), and a typical run of river project (b) (Micro-hydro power, 2008).*

Project Name	**Project Type**	**River**	**Installed Capacity (MW)**
Guarapo	Dam with reservoir	Alto Magdalena	140
Chillurco	Dam with reservoir	Alto Magdalena	180
Oporapa	Dam with reservoir	Alto Magdalena	220
Perícongo	Dam with reservoir	Alto Magdalena	80
El Manso	Dam with reservoir	Alto Magdalena	140
Veraguas	Dam with reservoir	Alto Magdalena	130
Bateas	Dam with reservoir	Alto Magdalena	140
Basilias	Dam with reservoir	Alto Magdalena	140
Tamas	Run of River hydro	Neiva	13.3
Las Ceibas	Run of River hydro	Las Ceibas	6
Santa Maria	Run of River hydro	Bache	9.9
Socorro	Run of River hydro	Bache	13.3
Venado	Run of River hydro	Venado	46-51[a]
Total	Dam with Reservoir		1,170
Total	Run of River hydro		88.5-93.5

[a]There are 2 options for development proposed for this project

Table 3-1 *List of all proposed hydropower projects included in this study, the rivers where they are to be located and their planned capacity in megawatts.*

Chapter 4 Hydropower impacts and benefits

4.1 Large hydropower

Large hydropower provides a significant and often reliable energy supply, and the development of large dams have been integral in the advancement of many nations' societies and economies. With increasing concern for climate change, many countries have turned to hydropower for a low carbon energy option and its contribution to "green economy" (Sneddon & Fox, 2008). However, large hydropower also results in widespread impacts from the dam and reservoir themselves as well as from their operating policies and there is debate over whether hydropower is a low carbon option for energy.

Development of a reservoir results in the displacement of people whose homes and towns are located near or at the location of a proposed reservoir as well as farmlands or other areas contributing to agricultural and industrial production (Chen, 2009; Duarte-Abadía et al. 2015, Zhang et al., 2015). This can lead to people losing their livelihoods, cultural identity, professions and subsistence food supply and loss of economic activities when they are forced to relocate (Duarte-Abadía et al. 2015; Cernea, 1997, Zhang et al., 2015). Reservoirs can also have other economic impacts apart from causing displacement. The period of filling a new reservoir has proven in some cases to be severely detrimental if not well managed. Poor reservoir operations while filling the Hidrosogamoso reservoir in 2014, located on the Sogamoso River, a tributary to the Magdalena River, resulted in a major decreases to streamflow downstream of the reservoir, killing fish and damaging the riparian area (“Alerta”, 2014; Duarte-Abadía et al. 2015). As previously mentioned, filling El Quimbo reservoir also led to significant fish kills downstream (“El Quimbo”, 2016).

Even after filling, the dam and reservoir itself can cause problems for fish and the ecosystem, dams and reservoirs can obstruct fish migration and sediment and nutrient transport (Li and Chen, 2008; Ziv et al, 2012; Angarita et al., 2015; Grill et al., 2015; Zhang et al., 2015). Silting, stratification and decomposition associated with the reservoir upstream of the dam can result in decreased water quality such as low dissolved oxygen (Kavurmaci et al., 2013). Decomposition in the reservoir and the resulting methane emissions has led to widespread debate over whether or not hydropower should be considered a low carbon energy source (ie. Demarty & Bastein, 2011; dos Santos et al., 2006; Fearnside, 2004). Zhang et al (2015) found that on average, emissions are greater from reservoirs in tropical zones, such as Colombia, than in boreal zones.

Large reservoirs can become stratified by temperature, dissolved oxygen and other water quality measures (Boehrer & Schultze, 2008; Chapra, 2008). For example, Betania is a stratified reservoir with a warmer epilimnion and a cooler hypolimnion (Plan de Ordenamiento Pesquero y Acuícola [POPA], n.d.). Within stratified reservoirs, water is mainly released from the bottom of the reservoir into the turbines to generate hydropower, thus water released downstream may be cooler than it would have been without the reservoir. However, when stratified reservoirs are full, and spill water over the spillway from the epilimnion reservoir layer, such downstream releases may be warmer than would have been otherwise.

Commonly, as decomposition occurs in the deeper waters of the reservoir, oxygen is used in the process resulting in anoxic conditions (Chapra, 2008; Fearnside, 2004). When such water is released from below through the turbines, it does not become reaerated until it is downstream of the dam (Fearnside, 2004), which is what has likely occurred with El Quimbo (CAM WEAP team meeting, January 8, 2016). Temperature, dissolved oxygen and other water quality fluctuations can cause serious health problems for fish, and can even make the water uninhabitable for some species, disrupting the ecosystem and also damaging fishing industries.

Apart from the dam and reservoir itself, flow regime changes downstream of the dam due to reservoir operations may alter a river's capacity to move sediment (Li and Chen, 2008) and nutrients (Angarita et al., 2015), affect water quality, or hinder migration and reproduction patterns of aquatic life such as fish (Jiménez-Segura et al., 2010; Angarita et al., 2015; Zhang et al., 2015). Typical reservoir operations result in retention of waters during the wet season and subsequent releases during the dry season, with the net result of reducing high flows and increasing low flows (Zhang et al., 2015). This can be useful in preventing potentially damaging floods to downstream communities or providing a more reliable water supply during droughts, but the natural variability in flows is essential to a river maintaining its structure and functions (Poff et al., 1997). Of concern here is the impact that such reservoir operations have on the natural variability of streamflows. Environmental flow requirements and operating rules can be implemented to reduce these impacts, however, meaning that both the negative effects to the ecosystem and the beneficial effects to mitigating extreme events, generating hydropower and others can be balanced based on the conditions and priorities of each system. Reservoir operations for flood prevention and water supply during droughts, could be particularly useful in Colombia considering the effects of La Niña and El Niño events. Although Colombia's tropical climate provides for sufficient rain throughout the year such that dry periods are not generally very dry compared to temperate regions, La Niña and El Niño events can still result in exceptionally wet and dry periods, respectively. Given the uncertainty of climate change and that Colombia recently experienced a historically severe drought ("Este fenómeno", 2016), dams and reservoirs may also provide a method to ease uncertainty and the impacts of extreme events.

4.1.1 The Colombian energy market's influence on large hydropower operations

Impacts of hydropower on stream flows may be especially severe in Colombia due to the complexity of the energy market and the resulting hydropower operating rules necessary to supply the majority of the country's energy supply. Because hydropower supplies over 60% of Colombia's energy supply, hydropower operators are required to supply base load energy as well as peak load and hydropower companies sell their power in multiple energy markets to do so. The daily energy market is run by the XM Compañía de Expertos en Mercados (XM). Every day, hydropower companies make an offer to XM which includes the hourly generating capacity and price for that energy which they are willing to supply for the following day. XM accepts the offer from the company with the lowest price first, and then the company with the next lowest price, until sufficient energy has been accepted to supply the estimated demand for the following day. This demand may include export to both Ecuador and Venezuela. The last company's offer required to meet the demand sets the payout price of power for that day. All hydropower companies with lower bids are paid at this same hourly price, however, companies who set their initial bid price too high, will not end up selling their power on that day. Additionally, to ensure sufficient energy supply and reasonable prices during the dry season and during El Niño years, longer term agreements, or contracts, are established requiring companies to sell consistent power to the Regulated and Nonregulated Markets. (den Ouden, 2015)

Most of the large dams are owned and operated by different private energy companies, and these dominate the energy market. Because of the competitive nature of the energy market, reservoir operators do not reveal their operating rules. If they were to do so, downstream reservoirs could use this information to their advantage. This competitive approach is promoted by the market because reservoirs are independently owned, and therefore competition keeps energy prices low. (den Ouden, 2015)

The overall result of the combinations of these markets and contracts can be detrimental to the river in terms of streamflow. Hydropower operations in Colombia typically result in "hydropeaking" or highly fluctuating releases from the reservoir (**Figure 4-1**a). As previously discussed, reservoirs are often operated to store water during times of naturally high inflows for future release during times of low natural flow. When operated in this way, a reservoir might provide flow regime benefits by eliminating flood damage caused by the largest flows while increasing the lowest flows and reducing stress on aquatic organisms from poor water quality and high temperatures, or other users when there is not sufficient water to meet all demands. **Figure 4-1**c shows that this is not the case for the operation of Betania where both extreme high flows and low flows are reduced for the purpose of increasing releases in a flow range most suitable for hydropower generation (median to high flows). There are many considerations which go into reservoir release decisions and hydropeaking operations, with the primary consideration being the competitive market. This determines whether a given hydropower company's energy will be purchased on a given day, and therefore whether the reservoir will release large stream flows to generate large amounts of energy, or just the minimum required to meet the long-term contract agreements. This rapid fluctuation in high and low flows disrupts the natural variability in flows below each dam and therefore the ecosystem and the species it supports. One study even found that hydropeaking may be linked to biologic changes in the reproductive organs of fish (Jimenez-Segura, 2007).

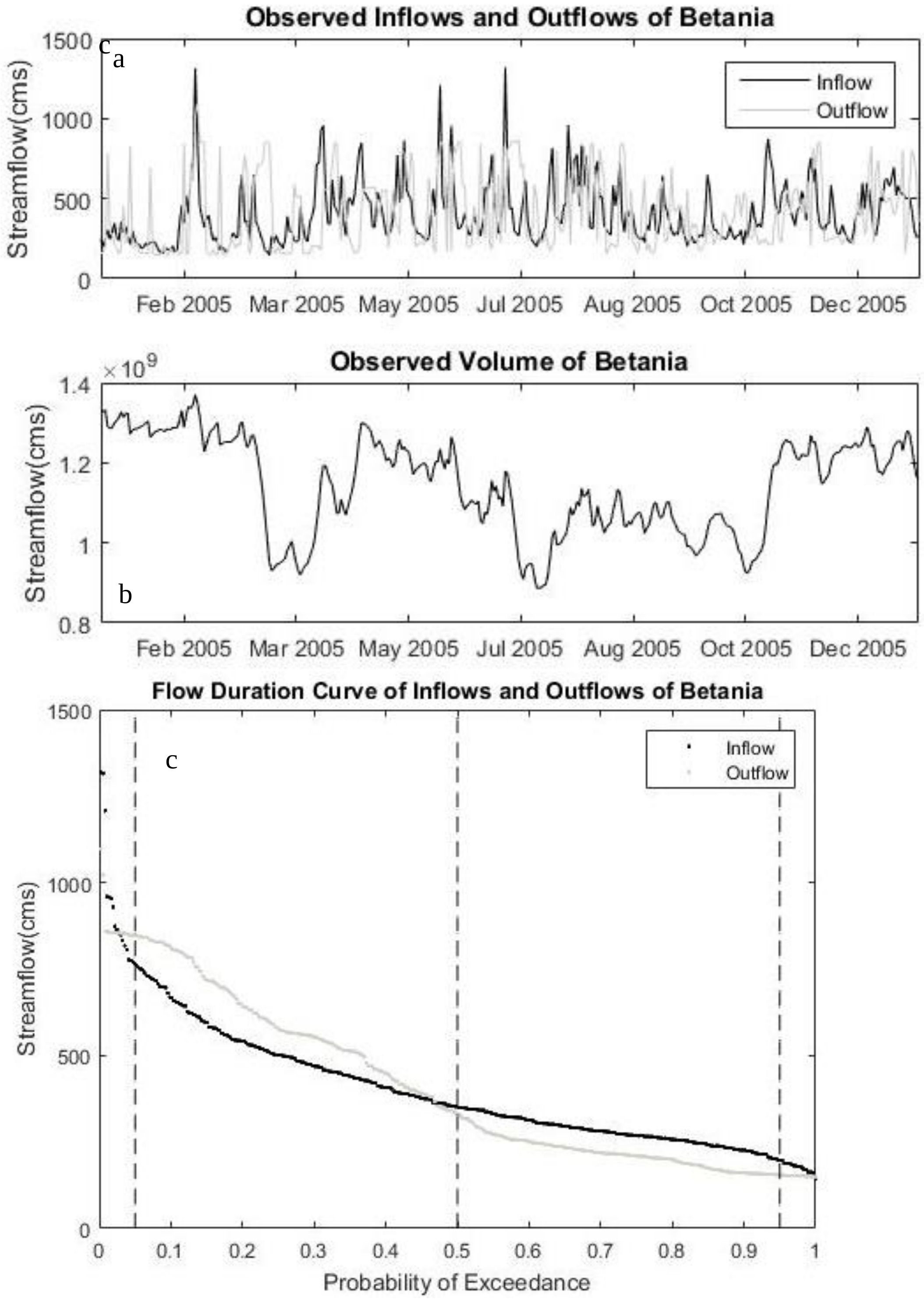

Figure 4-1. *An example of one year (2005) of historical inflows and outflows from Betania which demonstrate hydropeaking(a), the historical volume record of Betania (b) and the resulting flow duration curve of inflows and outflows(c).*

4.2 Small hydropower

Small run of river hydropower can be a potentially low impact solution for small energy needs, although, while some impacts can be mitigated, without consideration and planning, these impacts can still greatly disrupt the environment (Abbasi & Abbasi, 2011). Small projects can provide electricity to meet limited energy needs in remote areas that may not be connected to the power grid (Sachdev et al., 2015). At the same time, however, these areas have low energy demands and therefore may not be attractive areas for investment by developers (Morales, 2015). The typical efficiency, which is defined as the percentage of a given year that a plant is operating, of small projects, is only estimated to be 50% (Peña & Medina, 2010), and it has been stated that small hydropower has a large cost per unit generation (Sachdev et al., 2015). These considerations may lead some to believe small projects are unreliable or inefficient. Despite this, these types of projects have lower initial investment and operating and maintenance costs compared to large dams (Morales, 2015).

All solicitations for PCHs that the CAM has received are run of river type projects, which do not have a reservoir, and therefore do not result in many of the impacts that large dams do. Even still, operations of PCHs reduce streamflow in the section of river between where water is diverted and returns (**Figure 3-2**b) and may potentially completely dewater this reach during some parts of the year (International Energy Association [IEA], 1998). Complete or partial dewatering, as well as a weir or small dam at the intake may be an obstruction to migrating fish, which the International Energy Association mentions is often perceived as the most important ecological concern for small hydropower (IEA, 1998).

Apart from the most typical considerations for streamflows and fish, the CAM considers a variety of project specific impacts in their licensing process. One example is a proposed PCH on the Aipe River, a tributary to the Magdalena River, which the CAM recently denied a license for construction (CAM, 2015). Ultimately, the proposed location was in a very remote area which the CAM saw important to preserve because it was mainly pristine, had not yet been influenced by development, and the flora and fauna making up the ecosystem were not well studied (CAM, 2015). This is consistent with the World Wildlife Fund's findings which categorize the Magdalena basin, and specifically the dry forests (which describes the Aipe River basin and much of the Alto Magdalena basin) as its own ecoregion (Northern South America, n.d.). The reasoning for this is because although little is known about the biodiversity of the region, endemic species persist as a result of the Andes Mountains which keep the area isolated from other similar habitats (Northern South America, n.d.). This makes this area unique and important for conservation (Northern South America, n.d.), which is echoed by another study which considers the area surrounding the Alto Magdalena River a priority region for environmental conservation due to the high quantity of threatened and endemic vertebrate species (Forero-Medina & Joppa, 2010).

In the case of the project on the Aipe River, the project was proposed for a dry sandy area and the proposal did not include any mitigation for likely erosion from construction of the project and the road to the powerhouse, as well as continued use of the road after construction (CAM, 2015). Erosion and changes to sediment transport processes are common concerns for small hydropower projects (IEA, 1998). The intake for the town of Aipe's water source is downstream of the proposed site as well as diversion structures for rice irrigation, which would likely be negatively impacted by the sediment (CAM, 2015). Lastly, the project received significant backlash from the community (CAM, 2015). This is an example of how detailed the CAM is in the assessments of project impacts, but also how dependent the impacts of small hydropower can be on the detailed aspects associated with each project.

Other potential impacts of small hydropower projects may include pollution from biocides and chemicals used in piping and visual intrusion because many sites suitable for small hydropower are located in naturally beautiful areas. For projects that include a small dam or weir, flooding of the area results in the same issues as mentioned above with large hydropower, including displacement and disruption to the existing flora, fauna and ecosystem, and there is always a risk of dam failure, although much less of a concern with small projects than with large. (IEA, 1998)

4.3 Performance measures: connecting impacts and benefits to stakeholders' concerns

Performance measures are a way to connect the concerns of stakeholders, for example, for hydropower operators, revenue generated from hydropower, or for property owners, flood damage to property, with specific measurements such as average kilowatt hours of power generated and likelihood of a given flood event following development. Performance measures are essential estimates used to inform the decision making process with costs and benefits of different development plans which are important to the specific basin and population at hand. Because hydropower projects have a range of impacts: social, economic, and environmental, it is important to define a range of performance measures with the input of stakeholders within the basin. Including all stakeholders in the process of developing performance measures is important because stakeholders often do not equally bear the costs and benefits of hydropower development (Duarte-Abadía et al. 2015).

Developing performance measures for human needs and concerns is usually significantly easier than for ecosystem and species needs because they can be more easily quantified, often in economic terms. Determining the level of impacts that can be tolerated by ecosystems or specific species of interest requires extensive knowledge of the system and the species within it. In these cases, biological information can inform what measures may be important to maintaining ecosystem and species functions, and biologists or conservation organizations may act as the "stakeholder" on behalf of the ecosystem. In the Magdalena River, The Nature Conservancy (TNC) is actively working with the national and regional government entities and others to do this by contributing to the development of environmental flow requirements for hydropower (The Nature Conservancy [TNC], 2015a). Other work led by the Stockholm Environment Institute (SEI) and in collaboration with TNC has also contributed to this progress by providing quantitative tools to model streamflow and flooding in the Magdalena River basin as well as performance measures and adaptation strategies to reduce vulnerability in the face of climate change and other uncertainties (Stockholm Environment Institute [SEI], 2015).

The goal of this analysis is to contribute to the decision making process by assessing five performance measures, four of which measure hydrologic alteration, resulting from various development scenarios in the Alto Magdalena River basin. The performance measures used here are total power generating capacity, total disconnected river kilometers, and deviation of the Q5, Q50 and Q95 streamflow following development, compared to no development. The measures and the details of their calculations are explained in more detail in Chapter 5, below. Because of their expertise and knowledge in the area, TNC was an integral resource in developing the performance measures used in this analysis, which are based on existing knowledge of the migrating fish species inhabiting the Alto Magdalena River basin, as well as previously developed methodologies for measuring hydrologic alteration from the literature. Although migrating fish are not the only species directly impacted by hydropower development, this is the focus of this analysis because of the available information regarding their migration patterns in the Magdalena basin.

It is estimated that 15% of fish species in the Magdalena River basin migrate to some extent, and their general migration cycle and its connection to streamflow is well understood (Jiménez-Segura et al., 2014). Generally, fish migrate among wetlands, tributaries, and the mainstem of large rivers and their movement is dictated by seasonal changes in flows (Jiménez-Segura et al., 2014). In the upstream portion of the Alto Magdalena River basin, influence from the Amazon system drives a unimodal streamflow regime, with a single wet period (**Figure 4-2**). Downstream, the regime changes gradually to bimodal as the influence from the Amazon system diminishes and the oscillation of the Inter Tropical Convergence Zone dominates (**Figure 4-2**). Further downstream and outside of the study area (not shown in **Figure 4-2**), this becomes more prominent such that the period when the upper basin has water, is between periods when the lower basin has water (UPME, 2015).

During the periods of low flows, many fish leave the wetlands and swim upstream to find better water quality and to spawn. When flows are low, the fish are able to swim up the mainstem of the river. As flows increase, they seek refuge in tributaries. Here the adults spawn, and then allow the high flows to carry them and the fertilized eggs back down the mainstem to the wetlands. This acts as an incubation period for the eggs, which then hatch and mature in the safety of the wetlands during the duration of the wet period. Some fish carry out this process once over the year, and some may do this twice, once for each wet period (López-Casas el at., 2016). In order for this migration cycle to be successful, the fish need low flows that are sufficiently low over a sufficiently connected river to be able to migrate upstream, but not so low that water quality is compromised, followed by properly timed high flows that are high enough to carry the eggs downstream and deposit them in the wetland. (Jiménez-Segura et al., 2014)

The average distance traveled in this migration pattern varies by species, ranging from 0.8 km to 62 km (López-Casas et al., 2013) with the longest migration observed as 1,200 km (Jiménez-Segura et al., 2014). The elevation extent that species travel also varies by species, and the maximum is 2,000 m.a.s.l (Jiménez-Segura et al., 2014). Approximately 20 to 30 fish species inhabit rivers above 1,000 m of elevation, which characterizes the Alto Magdalena River basin and tributaries upstream of Betania (Jiménez-Segura et al., 2014). Although fewer species are found above 1,800 m.a.s.l., almost all of the fish at this elevation are endemic (Jiménez-Segura et al., 2014). This suggests that between the elevation extent travelled and the longest migration patterns, migrating fish could potentially reach the Alto Magdalena basin from lower in the river near the Mompos Depression. As previously mentioned, the Alto Magdalena River valley is also an area of particular concern for environmental protection beyond just endemic fish populations, but because there is also a high population of other endemic and threatened vertebrate species (Forero-Medina & Joppa, 2010).

The existing obstructions of Betania and El Quimbo make it difficult to understand natural fish migration patterns that would prevail in the absence of the dams, because there are not sufficient data that were collected regarding these patterns before Betania was constructed. Angarita et al (2015) discussed fish that migrate upstream from the Mompos Depression, located downstream of Betania and El Quimbo, near the confluence of the Cauca and Magdalena Rivers (**Figure 1-1**). These fish may already be impacted by the existing dams, and could be further impacted by additional dams. Rojas et al (2001) found nine native species in the Alto Magdalena river basin in a study evaluating the aquatic ecosystem in the department of Huila. Most of these species are listed as threatened to varying degrees (Mojica, et al., 2012). Of these nine species, three migrate to some extent (Rojas et al., 2001; Mojica, et al., 2012). Pareja et al., (2014) also found spawning, migrating fish in rivers upstream of Betania. Potentially, because of where Betania is located, and because there is sufficient flow variation and connected river upstream of it for migration, the reservoir itself can serve the purpose of a quiescent wetland in the migration patterns of these populations (Jiménez-Segura et al., 2014). Interestingly, in La Miel River, a large tributary to the Magdalena River, Jimenez-Segura et al (2014) found that a tributary which flows into La Miel River downstream of the Amaní-central Miel I dam serves as a migration route for fish in place of La Miel River, a behavior that has also been observed in the Paraná river basin (Antonio et al., 2007). Despite the fact that the dam is an obstruction to migration, fish are still able to carry out their life cycle processes.

Connectivity of a river is defined as “water deviated transfer of matter, energy or organisms within or between elements of the hydrologic cycle” (Pringle, 2003). Connectivity can have longitudinal, lateral and vertical components which connect upstream to downstream, the river to the floodplains, and surface water to groundwater, respectively, which are all important for a variety of functions (Grill et al., 2015). Longitudinal connectivity is specifically relevant to fish migration where fish rely on the ability to move freely between upstream and downstream portions of the river (Ziv et al., 2012), and therefore specifically relevant in the focus of this study. Throughout this analysis, “connectivity” will refer explicitly to longitudinal connectivity. Although the upstream and downstream portions of the study area are already fragmented by Betania and El Quimbo, the existence of fish both up and downstream suggest that the existing connectivity within these two sections are important to fish migration. The length or size of connected river required however, is difficult to determine. Some fish seem to be able to adjust to some degree of fragmentation, however, at some point development may lead to too much fragmentation such that the system can no longer support the species and their migration patterns.

Connectivity is a performance measure used by TNC in their work on the Magdalena River which is simply measured as the number of connected longitudinal river kilometers from the mouth of the river to the first dam encountered either on the mainstem of the river or in tributaries (Opperman et al., 2015). This quantity can then be compared among different development options. TNC’s “Hydropower by design” approach promotes strategically selecting dam placement to maximize the preservation of existing connectivity (Opperman et al., 2015). Here, TNC’s approach to connectivity is extended to include reaches both upstream and downstream of Betania and El Quimbo, and the performance measure used is the number of connected river kilometers lost due to hydropower development. In this analysis, connectivity is used to define a non-inferior set of development options. The non-inferior set is the set of project development options which simultaneously minimize connectivity lost while maximizing hydropower generating capacity. For a development option to be included in the non-inferior set, no other option can exist which results in less connectivity lost for the same gain in generating capacity nor one which results in higher gains in generating capacity for the same amount of connectivity lost. A detailed explanation of how these measures are calculated and assessed is given in section 5.2 below.

Apart from connectivity, the fluctuations in streamflow are also essential in triggering and allowing fish migration, among other important river processes such as sediment and nutrient transport. In an extensive literature review of studies of hydropower effects to fish populations worldwide and in Colombia, Jiménez-Segura et al. (2014) reveals that studies discussing the impacts of hydropower on the flow regime downstream and their linkage to fish in Colombia are lacking. In the situation of La Miel River, the tributary has sufficient flows that water downstream has the correct seasonal signals to trigger migration, despite the effects of hydropeaking from the dam operations (Jimenez-Segura et al., 2014). This suggests that some level of development may be tolerable by some species, so long as other rivers remain free flowing, but the extent to which this can be tolerated is not well understood.

Richter et al (1996) have developed a highly detailed and widely used method for quantifying the degree to which a given human activity has altered the flow regime of a river, called Indicators of Hydrologic Alteration (IHA). With this method, data from pre-impact and post-impact time frames are compared using 64 IHAs which can then be used to better understand the consequences of projects in terms of streamflow regime change. The IHAs are specific statistical measures of changes to the streamflow, evaluated at different time steps and built around five main considerations: magnitude, timing, duration, frequency, and rate of change of certain streamflow events. (Richter et al, 1996)

Olden and Poff (2003) have reviewed 171 indices or measurements quantifying alterations to streamflow, including IHAs. Their findings, along with the work of Gao et al (2009), demonstrate that many of these indices are redundant, may be unnecessary, or result in multicollinearity among indicators. Olden and Poff (2003) found that the IHAs can well represent the variability in streamflows, but not all are necessary for any single analysis, and therefore the number of indicators should be reduced based on the site-specific focus of the study. Vogel et al (2007) introduced performance measures, termed ecosurplus and ecodeficit, which quantify the shift in the flow duration curve between pre-impact and post-impact time periods. Flow duration curves are the cumulative distribution function of a record of streamflows, plotting stream flow measurements compared with their probability of exceedance, or the portion of the record that is equal to or greater than each measurement (Vogel and Fennessey, 1994). Gao et al (2009) demonstrate how calculating only ecosurplus and ecodeficit can explain much of the variability explained by the multitude of IHAs.

The importance of linking indicators to the needs of the ecosystem or species of concern is further echoed by the framework outlined in Poff et al (2010): the ecological limits of hydrologic alteration (ELOHA). This framework assesses the relationships between flow alteration and ecological response in order to provide methods to develop meaningful environmental flow standards (Poff et al., 2010). This is the methodology being applied in the Magdalena River basin (TNC, 2015a).

Three streamflow performance measures were developed for this study based on the above mentioned considerations: seasonal streamflow fluctuation is essential for migration and other functions in the Magdalena River, flow duration curves have great explanatory power for alteration to flows (Gao et al., 2009) and developing simple, easily communicated performance measures is important (Poff et al., 2010). The measures calculated here are changes to the Q5, Q50 and Q95 stream flows on the median annual flow duration curve (flows with an exceedance probability of 0.05, 0.5 and 0.95, respectively). A median annual flow duration curve is computed as the median of the n annual flow duration curves where each annual flow duration curve is computed from each of the n years of daily streamflow (see Vogel and Fennessey, 1994). A median annual flow duration curve represents a typical year of streamflow measurements in a river. A detailed explanation of these flow duration curves and performance measures is included in section 5.3.3. Although there is not sufficient information to confirm that these flows specifically are important to any one fish species or ecological function, they provide a method to analyze the changes to high, median and low flows, which are significant in migration and other functions.

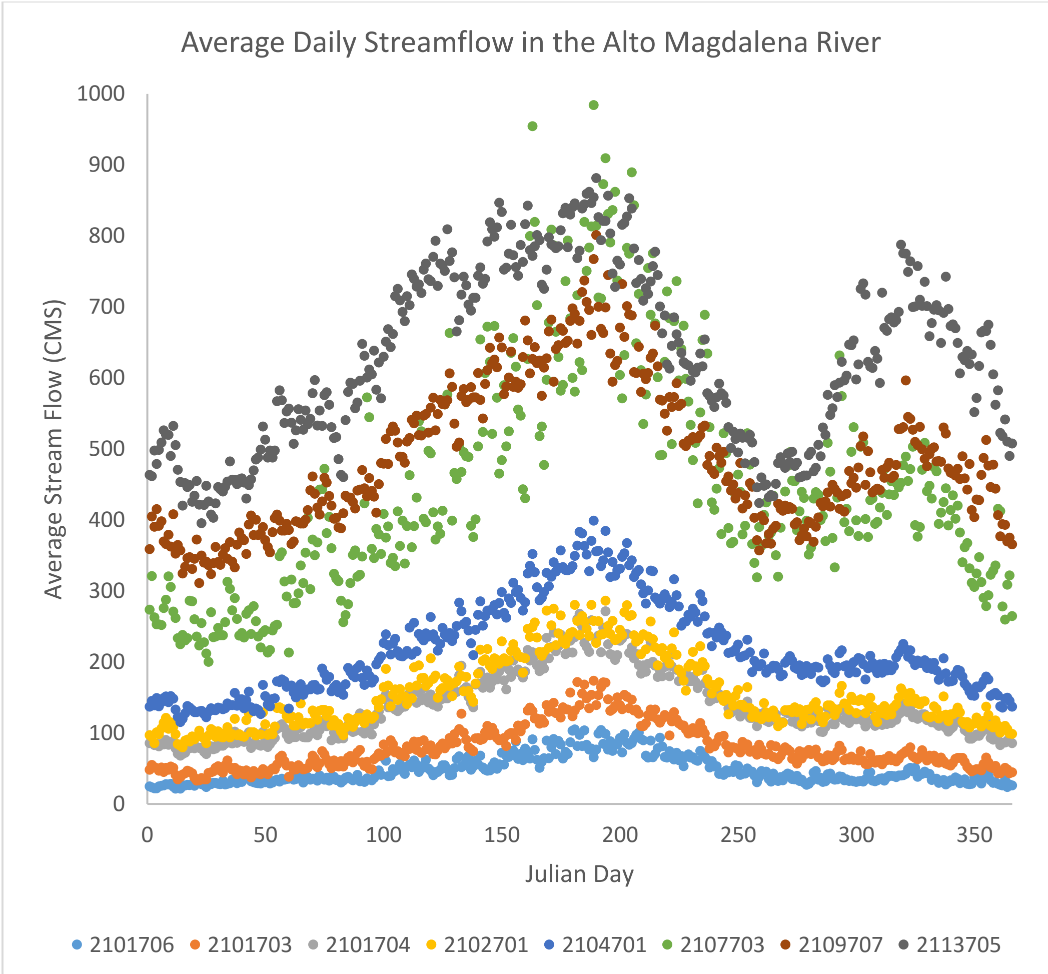

Figure 4-2. *Average annual streamflow along the mainstem of the Alto Magdalena River.*

Gauge numbers are listed from upstream (2101706) to downstream (2113705) across the bottom of the figure, and locations are shown in **Figure 5-3**.

Chapter 5 Methods

5.1 Study Outline

This analysis summarizes five performance measures resulting from scenarios of development of five proposed small and eight proposed large hydropower projects in the Alto Magdalena River basin:

1. Total power generating capacity, as the sum of the size of all projects considered in a given scenario, in megawatts

2. Total river kilometers disconnected with respect to the base case

3. Comparison of the Q5 streamflow following development, to no development, calculated as the difference between the median annual flow duration curves

4. Comparison of the Q50 streamflow following development, to no development, calculated as the difference between the median annual flow duration curves

5. Comparison of the Q95 streamflow following development, to no development, calculated as the difference between the median annual flow duration curves

Performance measures 3-5 are measured in the reach just downstream of Perícongo and Basilias. Performance measures 2-5 are each compared with performance measure 1 to present the tradeoffs between hydropower generating capacity gained and impacts incurred. The analysis aims to present these tradeoffs by addressing two key questions:

1. What is the non-inferior set of project combinations based on connectivity lost and megawatts gained and how do they compare?

2. How do the project combinations included in the non-inferior set compare in impacts to low, median and high flows in the upstream and downstream portions of the Alto Magdalena River basin?

5.2 Connectivity Analysis

In this analysis, connectivity is considered completely disrupted by all hydropower projects, despite their size or type. The stretches of river PCHs directly affected may be short, complete or partially dewatered in the reach between where water is diverted and returned to the river, yet these impacts may be a sufficient obstruction to migrating fish as well as a weir or small dam just downstream of the intake. Due to lack of sufficient information to determine how little water in the river is too little, or how tall a dam or weir is too tall for a fish to pass, for this analysis, any diversion or dam is considered a complete obstruction to connectivity.

Because two dams already exist in the Alto Magdalena River basin fragmenting the study area (**Figure 5-1**a and **Figure 5-1**b), and fish populations exist both up and downstream of these dams, it is assumed that under baseline conditions for connectivity, there are three separately connected sections (**Figure 5-1**b). The sections are located upstream of El Quimbo (which is already disconnected from the rest of the basin), between El Quimbo and Betania, (which is also disconnected from the rest of the basin, but is not further impacted by the projects considered in this study) and downstream of Betania (which is currently connected to the rest of the basin downstream) (**Figure 5-1**b). Connectivity lost is measured as the continuous river kilometers upstream of a new large or small project to the headwaters or to Betania, (if the new projects are downstream of Betania) within rivers of stream order two or greater (**Figure 5-1**c). Calculations for connectivity lost were done in ArcGIS using the HydroSHEDS database

(Lehner et al., 2008). Connectivity lost was computed from every possible combination of the eight, or fewer, large projects, 255 combinations in total (calculated with Equation 5-1). Connectivity lost from a final combination, full large hydropower development with all PCHs was also calculated. Efficiency for each individual project and each of the 256 project combinations was calculated as the ratio of total megawatts gained to connected river kilometers lost.

Equation 5-1

$$\sum_{r=1}^{8} {}_{8}C_{r}$$

Where:
r = the number of projects in a set

The non-inferior set of development combinations was computed based on size of the projects in megawatts versus connectivity, and streamflow impacts were only assessed for this set of combinations. This non-inferioir set of development options was determined based on connectivity instead of streamflow impacts because the obstruction to connectivity cannot be changed once a project is built, but reservoir operations and therefore impacts to streamflow can be adjusted once a dam is built.

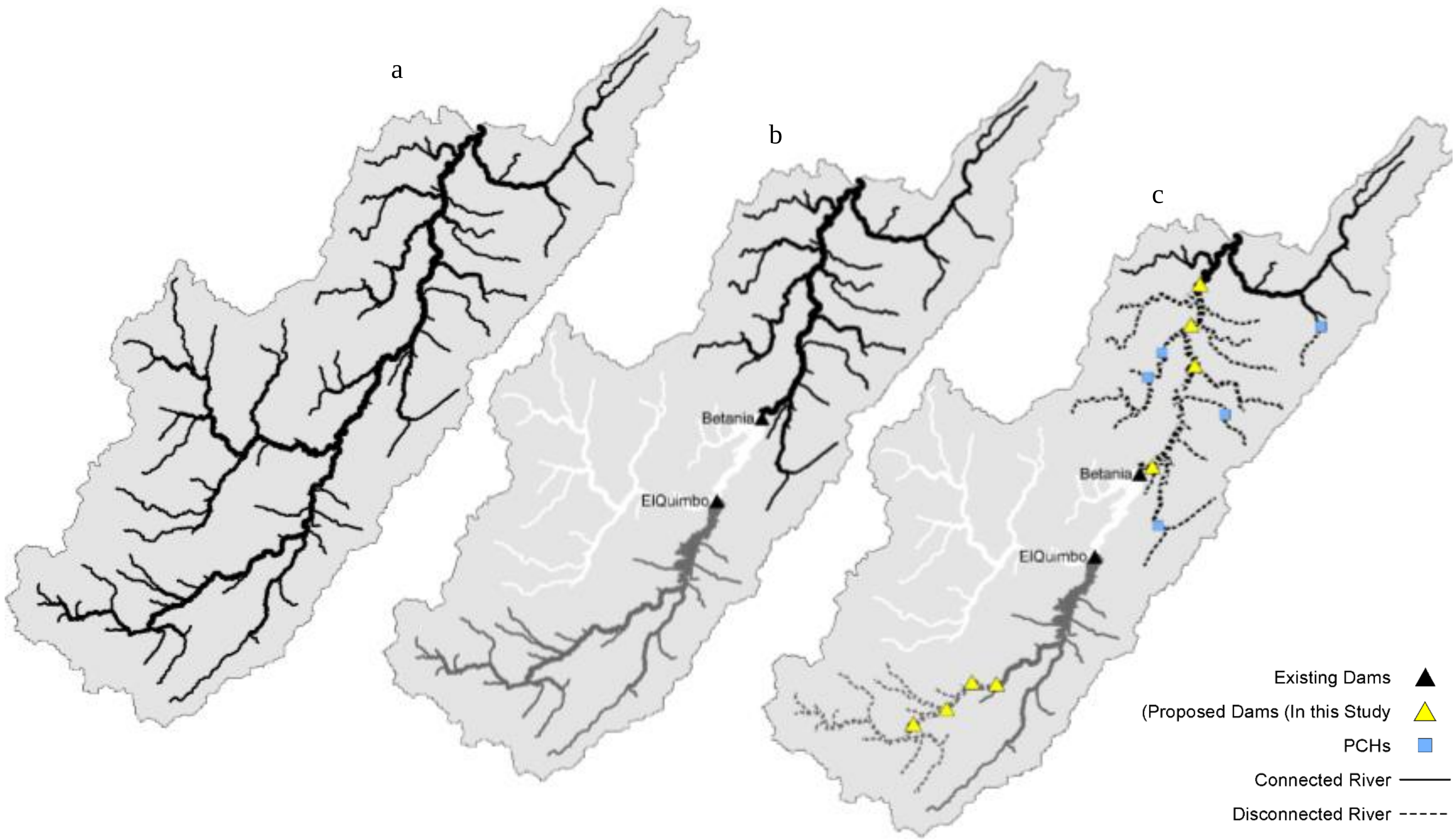

Figure 5-1. *Maps showing examples of the fully connected system, as would exist without Betania and El Quimbo (a) the three fully connected systems at current conditions (b) and a fully disconnected system with development of all projects (c).*

5.2.1 Hydropower project data

Data for the small hydropower projects was provided by the CAM (CAM, n.d.). The CAM received solicitations for eight projects total, however, location information, which is based on previous WEAP models developed by the CAM, was only supplied for five projects, thus only those five projects are included in this analysis (**Table 3-1**). Because the locations of the projects are based on previous WEAP models, they are not exact. Location of the large hydropower projects was provided as an Arc GIS shapefile by TNC. Size, in megawatts, of the large hydropower projects was provided by The Master Plan (**Table 3-1**, "The Republic", 2013)

5.3 Streamflow impact analysis

Water Evaluation and Planning System (WEAP), is a tool for water resource management developed by SEI. WEAP can be used to model the effects that a variety of changes within a watershed, such as land use changes, dam construction, reservoir operations and policy implementations may have on the water availability of a river in order to provide decision makers with informed predictions of how their decisions may affect a basin (Yates et al., 2005).

A WEAP model of the Alto Magdalena River basin, shown in **Figure 5-2**, was developed to assess the streamflow impacts of the scenarios of hydropower development included in the non-inferior set. WEAP has a variety of different methods which can be used to model streamflow. In this model, each inflow node contains inflow records which contribute incremental streamflow records based on the drainage area at that point. For the most upstream projects in the mainstem and tributaries which do not have inflow nodes, the full streamflow record from the location of that project is entered as the headflow of the river. The tributaries where the small hydropower projects are located are modeled separately from the mainstem of the river due to the methods used to fill in gaps in their streamflow records, which is explained in more detail below. These projects are included in the model for potential future use, where energy generation of the entire system may be assessed holistically, but were not used in this analysis for reasons explained below.

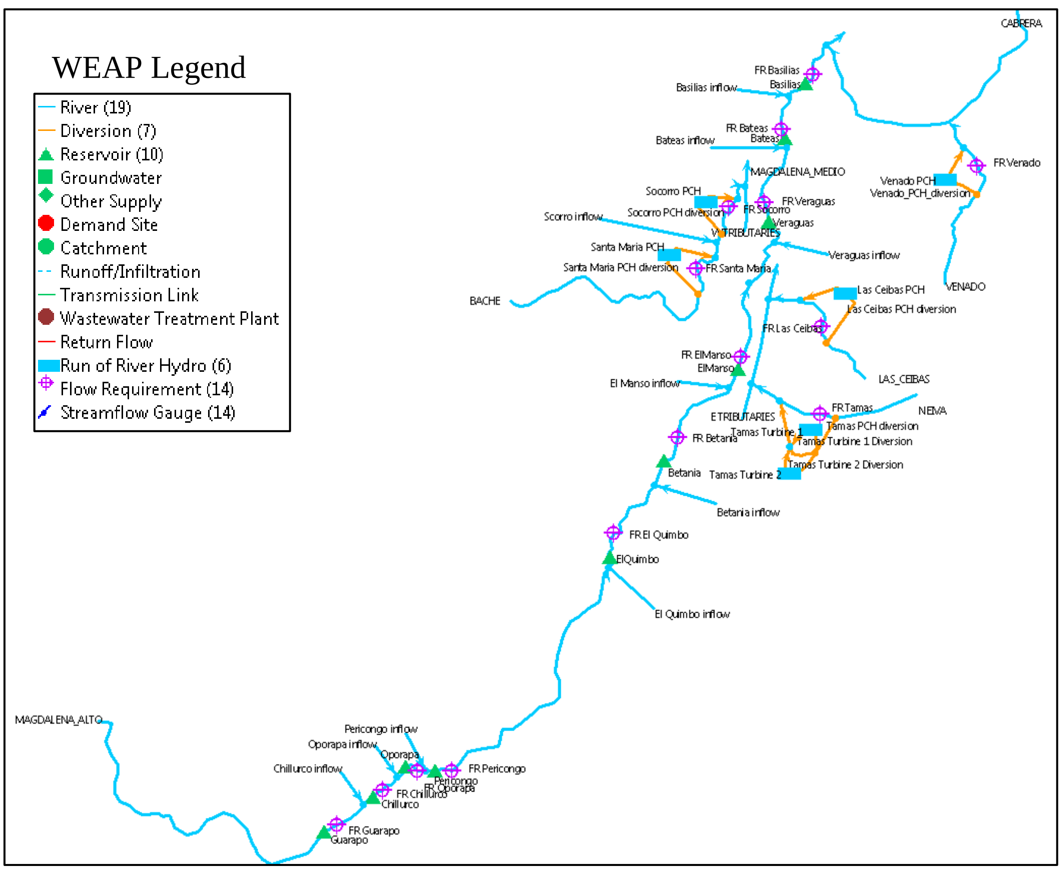

Figure 5-2. *Schematic from WEAP model.*

Blue lines labeled with capital letters are true rivers. Blue lines labeled as “inflow” are inflow nodes.

5.3.1 Mainstem streamflow records and large hydropower projects

5.3.1.1 Filling gaps in streamflow records

Daily streamflow data are made available by the IDEAM. Within the Alto Magdalena River basin, there are 29 streamflow gauges managed by IDEAM (Figure 5-3). Of those, historical records from all 8 of the gauges on the mainstem of the Magdalena River were used to develop the model, as well as data from some gauges on few tributaries. The PCHs were not included in the WEAP model because they do not have widespread streamflow impacts. Their impact on streamflow only extends to the short reach in the river between where water is diverted for power generation and returned back into the river.

For each gauge on the mainstem of the Magdalena River (**Figure 5-3**) some gaps existed throughout the daily historical record. To fill these gaps, two linear regressions were developed, one between the gauge of interest (the gauge whose record is being filled in) and the next upstream gauge, and one between the gauge of interest and the next downstream gauge. If the gauge of interest was the most upstream or downstream, or the next downstream gauge was one with an impaired record (downstream of Betania), the two regressions were constructed using the records from either another nearby gauge with a similar drainage area, or the next further upstream or downstream gauge. The regression equation exhibiting the best correlation (highest r squared value[1] and highest Nash Sutcliffe Efficiency (NSE)[2]) with the gauge of interest was primarily used to fill in gaps within the historical record of the gauge of interest. If there were concurrent periods of gaps between these two gauges, the other gauge's record and regression equation were used. If gaps still remained, a third regression was developed with the next best correlated gauge (either nearby or further upstream or downstream), and this process continued until all gauge records were filled in (**Table 5-1**). All regressions used to fill in these streamflow records exhibited an r squared value and Nash Sutcliffe Efficiency greater than 0.71. **Table 5-1** shows details of which gauges were used to develop regressions, their relationship with the gauge of interest, and r squared values of the regressions.

Gauge 2107703, located just downstream of El Quimbo (**Figure 5-3**) exhibited streamflow data that were an order of magnitude higher than any other data in the record in 2008, and were not correlated with data from gauges neither up nor downstream. Other researchers confirmed the data from this gauge is often inconsistent. For this reason, data in 2008 from this gauge were eliminated and data this year were filled in using the methodology explained above.

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[1] The r squared describes the collinearity between the modeled and observed values. A perfect model will have an r^2 value of one, and a value of zero means there is no linear relationship between the modeled values and the observations. (Moriasi et al., 2007)

[2] Nash Sutcliffe Efficiency (NSE) is a measure of the residual variance compared to the observed data variance. This value is computed by summing the squared differences between each simulated data point and the corresponding observed data point, and normalizing over the sum of the squared difference between each of the observed data points and the observed mean. This value is subtracted from one. A perfect model will return an NSE of 1 and a negative NSE indicates that the mean of the observations is a better predictor than the model. (Moriasi et al., 2007)

Once all historical records were filled in for the mainstem gauges, the records were scaled using the drainage area of each proposed hydropower project as shown in **Equation 5-2**. This equation calculates streamflow at an ungauged location between two gauge locations based on a linear interpolation between the runoff per square kilometer of the upstream and downstream gauged areas.

Equation 5-2

$$\frac{Q_{HP}}{A_{HP}} = \frac{Q_{US}}{A_{US}} + (\frac{Q_{DS}}{A_{DS}} - \frac{Q_{US}}{A_{US}}) * (\frac{A_{HP} - A_{US}}{A_{DS} - A_{US}})$$

Where:
Q_{HP} = Streamflow record at the location of the hydropower project
A_{HP} = Drainage area upstream of the hydropower project
Q_{US} and Q_{DS} = Streamflow records from the upstream and downstream gauges, respectively, and
A_{US} and A_{DS} = Drainage areas above the upstream and downstream gauges, respectively.

The historical record for the location of each project (Q_{HP}) developed with **Equation 5-2** were then adjusted using **Equation 5-3**, to develop a daily record of inflows at each hydropower location (QI_{HP}). “Inflow” is used here to mean the incremental streamflow that is gained in the river between each project. WEAP, like other water resources planning software, requires inflows to be non-negative. Where the inflow records, (QI_{HP}) contained negative values, the negative flows for each time step were set equal to zero and passed upstream by adding the negative value to the next upstream project’s inflow record at the same time step. This approach retains incremental flow losses in the overall water balance, while meeting the software requirements of non-negative inflow. Negative inflows were passed upstream until all negative inflows were eliminated from the records.

Equation 5-3

$$QI_{HPn} = Q_{HPn} - \sum_{1}^{n-1} Q_{HP}$$

Where:
QI_{HP} = Inflow record for each hydropower project
*n = Number of the hydropower project (**Table 5-2**)*
Q_{HP} = Scaled streamflow records for each hydropower project (from Equation 5-1).

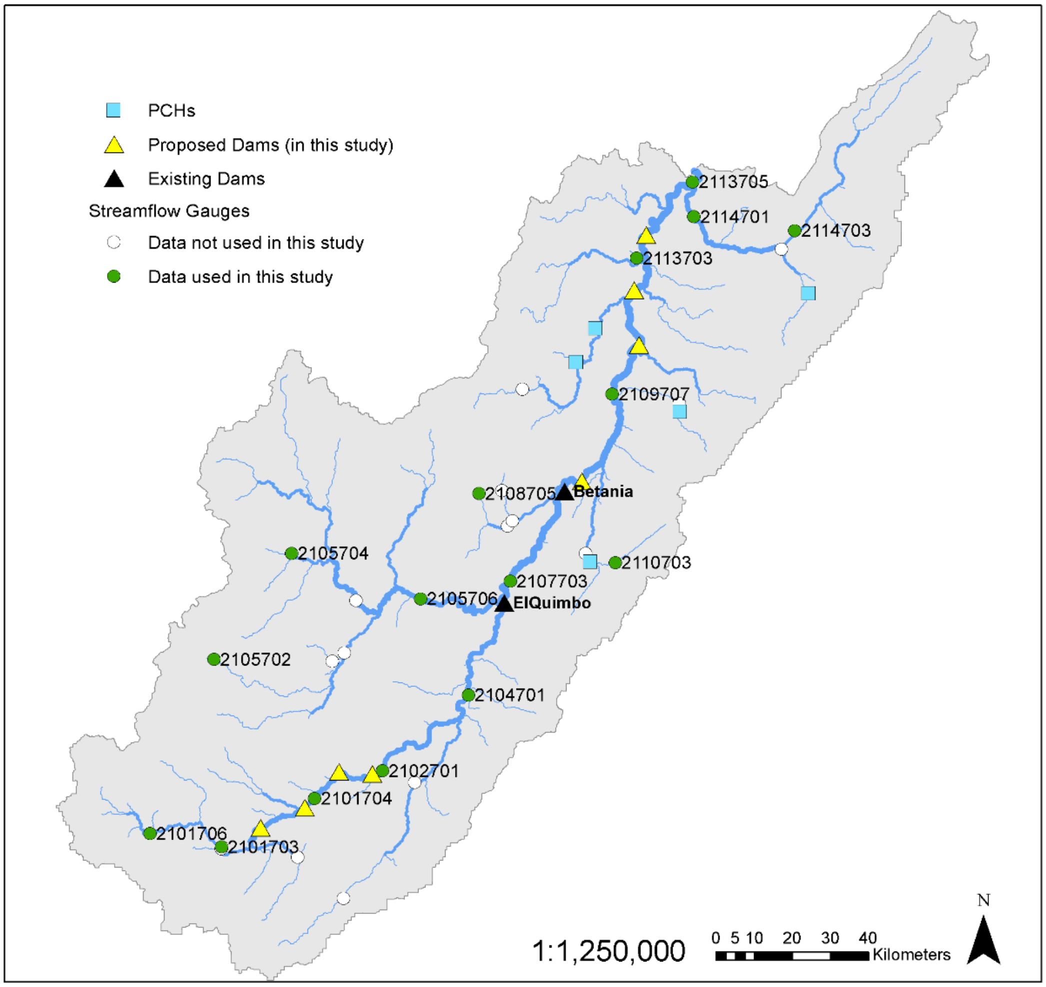


***Figure 5-3.** Map of streamflow gauges relative to hydropower projects*

Mainstem Gauge Regressions

Gauge of interest	Regression 1 Gauge	r^2, NSE	Relationship	Regression 2 Gauge	r^2, NSE	Relationship	Regression 3 Gauge	r^2, NSE	Relationship
2101703	2101704	0.808	ds	2101706	0.745,0.750	us			
2101704	2102701	0.881	ds	2101703	0.808	us			
2102701	2104701	0.885	ds	2101704	0.881	us			
2104701	2102701	0.885	us	2107703	0.823	ds			
2107703	2105706[a]	0.845, 0.846	nearby	2104701	0.823	us	2102701[b]	0.771	next us
2109707[c]	2113705[c]	0.714, 0.713	ds						
2113705[c]	2113701[c]	0.746	ds	2109707[c]	0.714	us			

Tributary Gauge Regressions

Gauge of interest	Regression 1 Gauge	r^2	Regression 2 Gauge	r^2	Regression 3 Gauge	r^2	Regression 4 Gauge	r^2	Regression 5 Gauge	r^2	Regression 6 Gauge	r^2	Regression 7 Gauge	r^2
2114705	2105704	0.25	2105702	0.21	2105701	0.92	2114703	0.10	2108705	0.12	2114701	0.10	2104701	0.07
2114701	2114703	0.69	2105706	0.41	2104701	0.36	2102701	0.34						
2111708	2113705	0.13	2114701	0.08	2110703	0.08	2114703	0.08						
2112702	2113703	0.20	2113705	0.17	2108705	0.16								
2110702	2107703	0.30	2102701	0.21										

[a] nearby gauge with similar drainage area was used because downstream gauge had impaired record

[b] Next upstream gauge was used because downstream gauge had an impaired record

[c] Gauge records are impaired from 1987-2010

Table 5-1. *List of regressions used to fill in gaps in records from main stem and tributary gauges, their relationship to the gauge of interest, and the correlation between the two gauges (r2, Nash Sutcliffe Efficiency value (NSE)).*

"Us" means the next upstream gauges from the gauge of interest, "ds" means the next downstream gauge, "nearby" refers to a nearby gauge with similar drainage area, "next us" refers to the second gauge upstream of the gauge of interest. The relationship is not listed for tributary gauges as they are not geographically related. While r^2 and NSE values were not the same, often they were equal when rounded. In these cases, the value is only listed once but represents both statistics.

5.3.1.2 Adjusting impaired streamflows downstream of Betania

Gauges 2109707 and 2113705 are both located downstream of Betania (**Figure 5-3**). It was assumed that flows at both of these gauges have been impaired by the operations of Betania since it began operating in 1987. In order to preserve the flow regime change from upstream to downstream (**Figure 4-2**), I chose not to scale unimpaired streamflow records from upstream of Betania for the downstream reaches. Instead, to correct flows in 1987-2010, I developed the flow duration curve using all impaired data from each gauge in 1987-2010, and unimpaired data from each gauge from 1972-1987 (**Figure 5-4**a and **Figure 5-5**a). This is a steady state flow duration curve because it includes flows from multiple years of record. I divided the curves into 20 bins containing 5% of the data points in each bin. The last bin, containing values with an exceedance probability between 0 and 0.05, was divided further into two bins to ensure a good fit of the adjusted high flows to the unimpaired data (**Figure 5-4**a and **Figure 5-5**a).

The difference between the maximum values in each bin from the impaired flows and the unimpaired flows was calculated and the same was done for the minimum values in each bin. The difference between maximum and minimum values within each bin was linearly interpolated to estimate the difference between the impaired and unimpaired flows for each data point. This difference was added to the unimpaired flows. The goal of this methodology is to adjust the impaired flow duration curve to match the shape of the unimpaired curve to represent overall flow trends in the record (**Figure 5-4**a and **Figure 5-5**a).

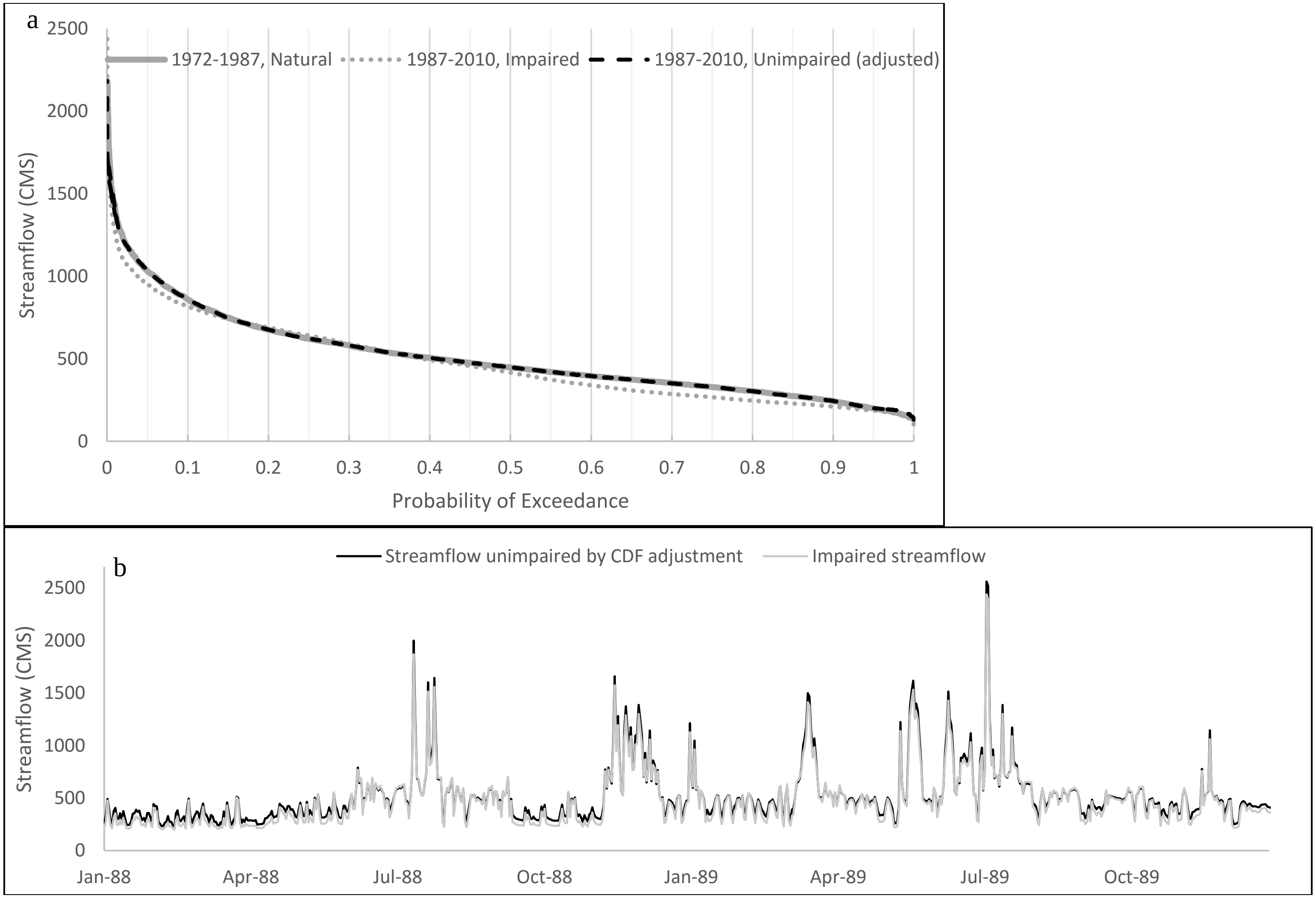


Figure 5-4. *Flow duration curves of impaired records, naturally unimpaired records, and unimpaired records (1972-2010) (a) and comparison between impaired and unimpaired streamflow records (1986, unimpaired, to 1987, impaired) for gauge 2109707.*

Unimpaired data were adjusted based on methods described in Section 5.3.1.2.

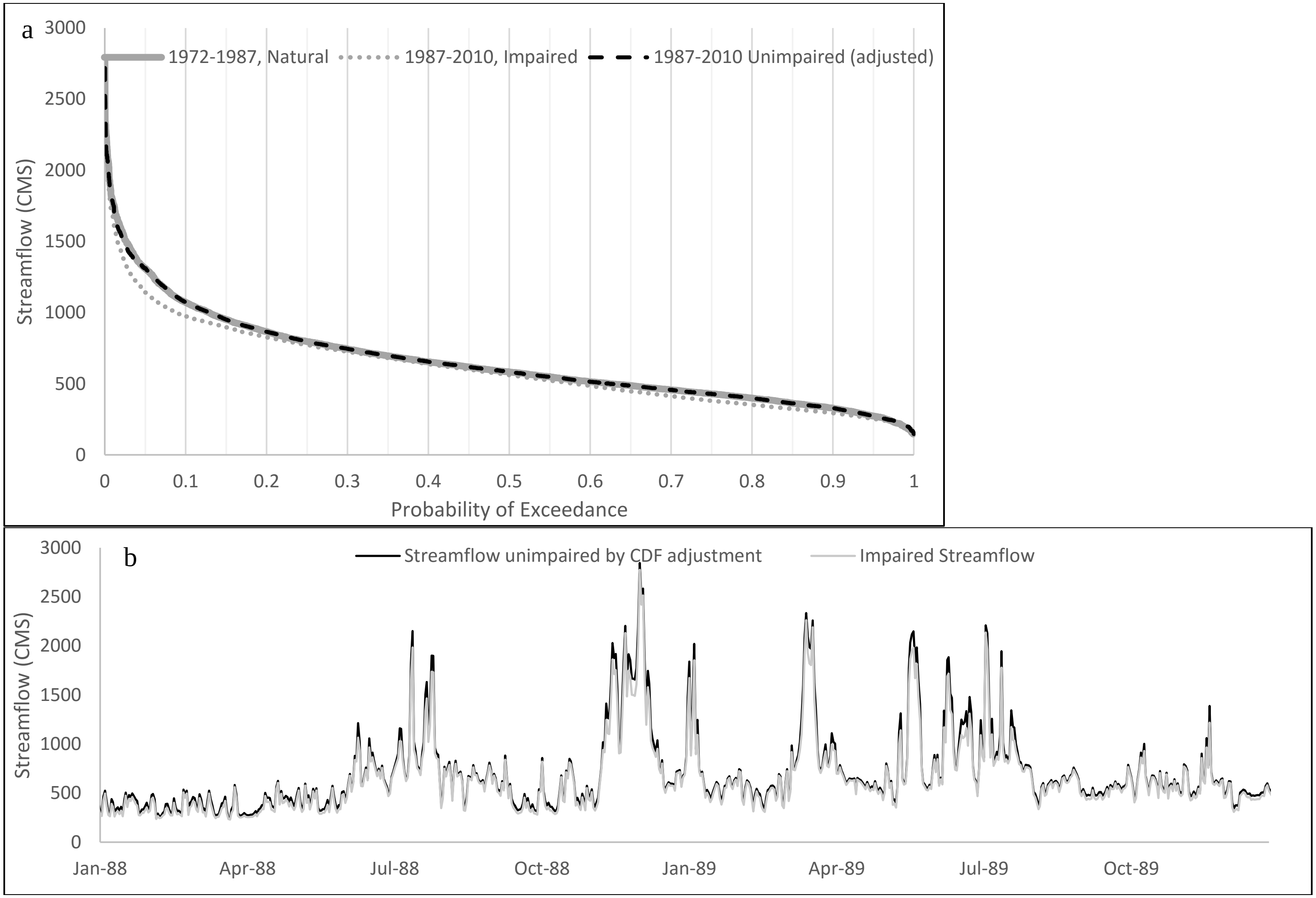


Figure 5-5. *Flow duration curves of impaired records, naturally unimpaired records, and unimpaired records (1972-2010) (a) and comparison between impaired and unimpaired streamflow records (1986, unimpaired, to 1987, impaired) for gauge 2113705.*

Unimpaired data were adjusted based on methods described in Section 5.3.1.2

5.3.1.3 Large hydropower project data

Reservoir and hydropower data for the proposed large projects on the mainstem of the Magdalena River included in the WEAP model are based mainly on the Master Plan ("The Republic", 2013). Some assumptions were made in order to integrate the information provided in the Master Plan with that required in WEAP. **Table 5-2** shows the values provided in the Master Plan and how they were used to fill in the parameters of the reservoir and hydropower operations in the WEAP model. The maximum turbine flow for all projects except Betania and El Quimbo was calculated using **Equation 5-4**. I assumed an efficiency of 0.9 because when I back-calculated the known maximum turbine flow with other known data for El Quimbo and Betania using **Equation 5-4**, an efficiency of 0.9 returned the correct flow.

Equation 5-4

$$P = h * Q * \gamma * e$$

Where:
P=Installed Capacity in Watts
*h=head in meters, (Backwater height of dam, **Table 5-2**)*
Q=Max turbine flow in m^3/s
γ*=specific weight of water, 9810* N/m^3
e= efficiency, assumed as 90%

Storage elevation curves for Betania and El Quimbo were provided by The Nature Conservancy. The data for Betania was originally sourced from EMGESA, the hydropower company operating the reservoir, and the data for El Quimbo were generated using Arc GIS and a digital elevation model from SRTM90 (Jarvis et al., 2008). Storage elevation curves for the proposed projects were developed under some simple assumptions. The maximum and minimum operating levels and volumes of Guarapo, Oporapa and Chillurco were provided in the Master Plan (Table 5-2). For these reservoirs, a linear storage elevation curve was assumed which means the shape of the top portion of the reservoir is assumed to be a cylinder. Although this is not likely, this represents only approximately the upper fifty percent of the reservoir by volume, and therefore only the top portion of the storage elevation curve. The portion of the curve for both Betania and El Quimbo that represents the top fifty percent of the volume of each of these reservoirs is close to linear (**Figure 5-6**). This assumption is reasonable given the investigation of this study, which is reservoir operations of hydropower. Because these reservoirs will only be operated over this top fifty percent of the reservoir, and under reservoir operations, the volume should not go above or below these volumes, this relatively linear portion of the curve is all that is necessary for this analysis. Because an elevation for an empty reservoir is required in WEAP, I assumed that these reservoirs have a volume of $0m^3$ at the elevation of the bottom of the dam. This elevation was determined by subtracting the backwater elevation of the dam from the full supply level (Table 5-2). The synthetic curves developed for this analysis are shown in **Figure 5-7**.

Only maximum reservoir elevation and area were provided for Perícongo, El Manso, Veraguas, Bateas and Basilias. For similar reasons as previously mentioned, I assumed a cylinder shape for these reservoirs and therefore their volume elevation curves are also linear (**Figure 5-7**). The maximum operating volume is calculated as the reservoir area at full capacity multiplied by the depth of the regulation storage, which, for all of these reservoirs is 2 meters as indicated by the Master Plan (**Table 5-2**, **Figure 5-7**). These reservoirs have a large area and therefore the plan indicates that they should only be operated within 2 meters of elevation above the inactive storage to avoid flooding nearby towns (“The Republic”, 2013). The minimum operating volume as well as the inactive storage volume are assumed 0 cubic meters. Because the reservoir volume cannot drop below the minimum operating level, the volume of the inactive storage below this level is irrelevant in this analysis and therefore it is reasonable to set this value equal to zero (**Figure 5-7**).

WEAP Parameter	Master Plan Parameter	Project Number: Project Name									
		1: Guarapo	2: Chillurco	3: Oporapa	4: Perícongo	5: El Quimbo[a]	6: Betania[a]	7: El Manso	8: Veraguas	9: Bateas	10: Basilias
Reservoir Parameters											
	Full Supply level /Average Annual Discharge (%)[b]	4.1	8.4	6.3		22.7	10.1				
	Res area at full supply level (km^2)	6.51	9.07	7.61	2.23			5.77	9.74	22.31	23.72
Top of cons (m.a.s.l.)	Full supply level (m.a.s.l.)	1220	1125	1015	870	720	561.2	485	420	399	378
Top of cons (Mm^3)	Storage at full supply level (Mm^3)	152.0	358.0	287.0	4.5[c]	1824.0	1488.2	11.5[c]	19.5[c]	44.6[c]	47.5[c]
Top of inactive (m.a.s.l.)	Min operation level (m.a.s.l.)	1205	1105	995	868	665	523.4	483	418	397	376
Conservation zone + Buffer zone (Mm^3)	Reg storage (Mm^3)	75	184	126							
	Depth of Reg Storage (m)	15.0	20.0	20.0	2.0	55.0	37.8	2.0	2.0	2.0	2.0
Top of inactive (Mm^3)	Storage at full supply level-Reg storage (Mm^3)	77	174	161	0[c]	604	125.8	0[c]	0[c]	0[c]	0[c]
	Backwater height of dam (m)	95	110	117	41	151	95	22	22	22	22
Tailwater elev (m.a.s.l.)	Full supply level-Backwater height of dam (m.a.s.l.)	1125	1015	898	829	577.4	489.2[d]	463	398	377	356

Hydropower Parameters											
Installed capacity (MW)		140	220	220	80	400	540	140	130	140	140
Annual generation (GWh/yr)		774.0	1190.0	1190.0	432.0	2216.0	1832.0	723.0	723.0	779.0	787.0
Max turbine flow (m3/s)	See Equation 5-4	166.9	226.5	213.0	221.0	320.0	850.0	720.8	669.3	720.8	720.8

[a]All data was provided by The Nature Conservancy except tailwater elevation for Betania (see d below).

[b]Ratios for most reservoirs is not provided because storage at full supply level was not supplied in the Master Plan (see c below).

[c]Values were not included in the Master Plan and were calculated assuming the reservoir holds the shape of a cylinder in the top 2 meters that are available for hydropower use. Inactive storage is not needed for the analysis and therefore was assumed 0. The actual size of these reservoirs is larger.

[d]This value was back calculated with other known data using Equation 5-4.

Table 5-2. *Large hydropower projects with reservoirs included in this study and data associated with them.*

All data was sourced from the Master Plan or calculated from values provided within the Master Plan, unless otherwise noted. “Reg” is regulation, “cons” is conservation, res” is reservoir, “elev” is elevation. Projects are listed from upstream (1) to downstream (10).

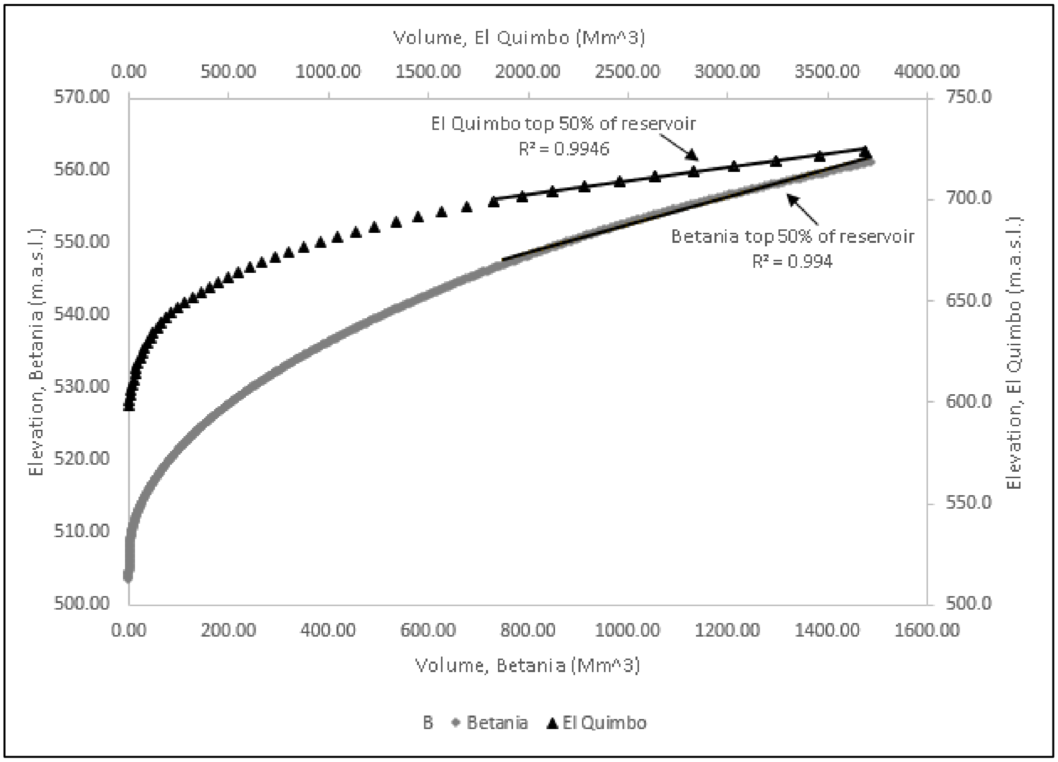


Figure 5-6. *Storage elevation curves for Betania and El Quimbo.*

Trend lines show the linear fit to the portion of the curve representing the top 50% of the reservoir by volume.

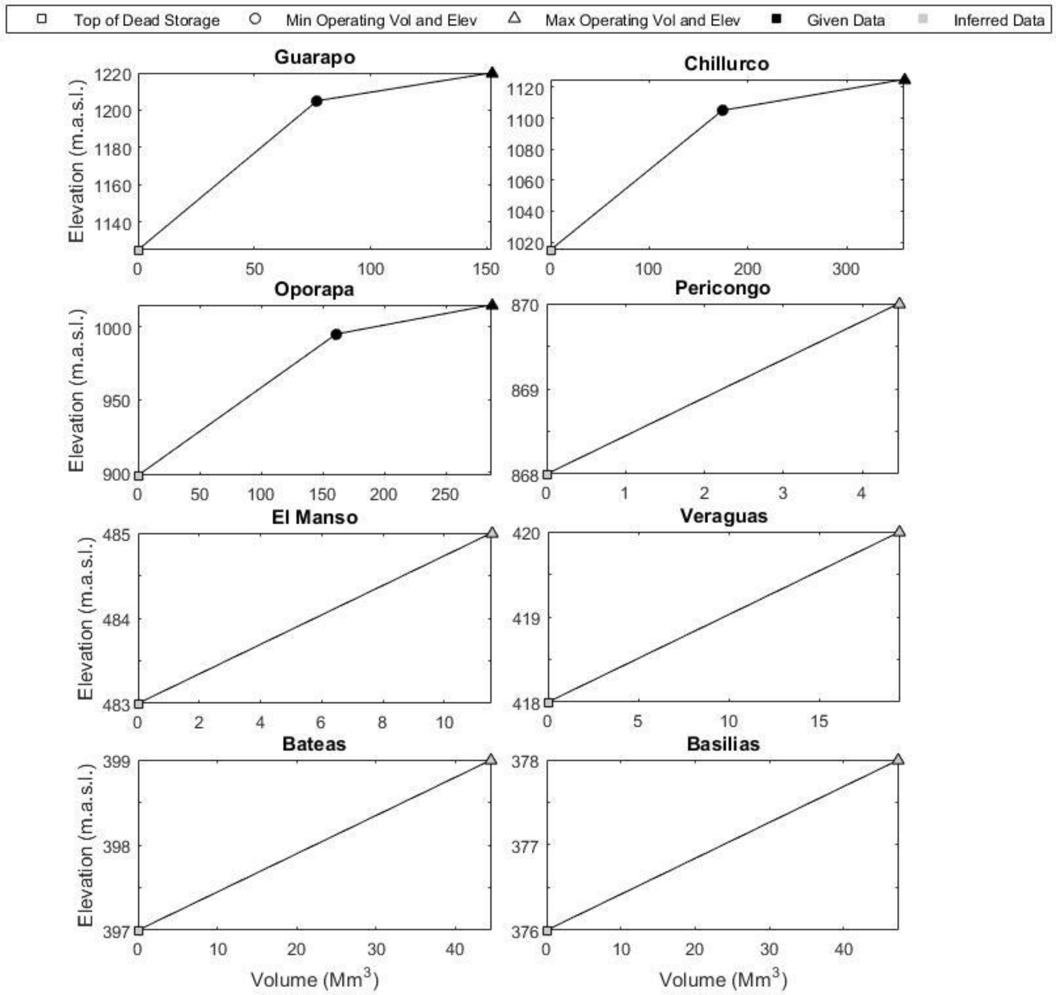


Figure 5-7. *Storage-elevation curves developed for all large hydropower projects included in this study.*

5.3.1.4 Reservoir operation simulations

As was previously explained, the complex energy market and reliance of the country on hydropower for the majority of its electricity supply makes for environmentally detrimental and non-transparent reservoir operations. One of the main performance measures included in this analysis is the difference between the flow duration curve following reservoir construction and the flow duration curve corresponding to no reservoirs. Because the performance metrics rely on the flow duration curve, reservoir operating rules were developed for Betania which replicate the flow duration curve of recorded outflow data from the reservoir from 2003 to 2010 (**Figure 5-9**).

Qualitative observation of historical flow duration curves for the inflows and outflows of Betania (XM, n.d.), such as that shown in **Figure 4-1**, reveals that for approximately the lower third to the lower half of the curve (~0.5 to 1 exceedance probability, which varies by year (**Figure 5-9**), the curve is relatively linear, with a very low slope (ranging only ~100 cms across this section of the curve) and remains much lower than the curve for inflows (**Figure 4-1**, **Figure 5-9**). This suggests that for one third to half the days in the year, Betania releases an average discharge that is almost as low as, and sometimes lower than the lowest flows in the record. This is different from the results of reservoir operations included in other studies, where low flows are generally increased by hydropower operations (Gao et al., 2009; Angarita et al., 2015; Zhang et al., 2015). This may be explained by the complex energy markets and the contract that the operators of Betania are bound by. Betania is required to supply at least 60 MW of power each day even if additional power is not sold on the daily market (H. Angarita, Magdalena Hydrologist, TNC, personal communication, January 13, 2016). Based on **Equation 5-4**, 219 cms of flow through the turbine is required to generate 60 MW when the reservoir is at the minimum operating level, just above inactive storage, and 103 cms is required when the reservoir is full. It may be that during dry periods, or on a given day when the offered energy is not purchased in the daily market, operators will only release between 103 and 219 cms to meet the minimum energy generating requirement, and that these circumstances occur on one third to one half the days of the year, filling out the lower section of the flow duration curve.

Further examination of these flow duration curves shows that moving from x=1 to x=0, past the lower section of the curve, the slope sharply increases until the y-value reaches about 850 cms (**Figure 4-1**, **Figure 5-9**). This section may be filled with days when Betania sells energy on the daily market. Once 850 cms is reached, the curve planes off again (**Figure 4-1**, **Figure 5-9**). The maximum turbine capacity of Betania is 850 cms, which explains why the curve flattens out at this y-value. On these days, Betania is generating at maximum capacity. I used these observations in developing reservoir operating rules with the intent to replicate the three sections in the flow duration curves of modeled flows.

In addition to examination of historical flow durations curves, previous work by den Ouden (2015) was considered, which demonstrates that outflows from a large reservoir in another part of the Magdalena River basin are largely correlated with lagged volume and inflows (volume and inflows from previous time steps), and only a small part of the outflow variability is explained by the market pricing. This likely has to do with whether the electricity from the reservoir was bought in the spot market on any given day, among other things. Just because the reservoir is full and has a large capacity to generate electricity, does not mean the operators offered it at the right price. If the electricity is not purchased by the market, the operators may only release the minimum contracted requirement. There is also a significant amount of situational information included in real-time decisions that is not included in this model or the WEAP model such as weather predictions, spikes or low periods in energy demands and long term market agreements.

Considering all of this information, reservoir operating rules were developed based on lagged storage volume, to minimize the difference between the modeled and measured annual flow duration curves from 2003 to 2010 and capture hydropeaking by adding a randomness to the outflows. The reservoir operating rules were developed using only data from Betania. The reservoir was divided into four volume thresholds (**Figure 5-8**). The maximum operating zone is between the maximum volume of the reservoir and 85% of the maximum volume. The target zone is between 43% and 85% of full, and the buffer zone is between the inactive zone and 43% full. Outflow at each daily timestep is determined based on the volume of the previous timestep and a random variable between the reservoir release thresholds (**Equation 5-5**). For example, if the reservoir volume at the previous timestep is within the maximum operating zone, the reservoir will release between 25 and 100% of its maximum turbine capacity, calculated as a random number between 0.25 and 1, multiplied by the maximum turbine flow (**Figure 5-8**, **Equation 5-5**). Each daily release falls between the upper and lower reservoir release thresholds (**Figure 5-8**) based on a uniformly distributed random number (**Equation 5-5**), which is generated at each timestep, for each reservoir, to replicate the seemingly randomness of streamflow releases associated with hydropeaking (**Figure 4-1**).

The volume and reservoir release thresholds (**Equation 5-5**, **Figure 5-8**) are a result of some calibrating to find the values which resulted in annual flow duration curves of outflows from Betania that best represent historically measured flows (**Figure 5-9**). These thresholds were manipulated until each year's modeled flow duration curve fit the historic flow duration curve for each year between 2003 and 2010. During calibration it was observed that manipulating the reservoir release thresholds mainly shaped the flow duration curve allowing the three sections observed in the historical data to be replicated (**Figure 4-1**, **Figure 5-9**). Adjusting the volume thresholds had less impact on the flow duration curve, but controlled between which volume thresholds the modeled volume tended to stay and how much it fluctuated between volumes. Goodness of fit was measured as the square root of the mean of the squared errors (RMSE) between the modeled and observed flow duration curves at Q5, Q25, Q50, Q75 and Q95 for each year. Excel's nonlinear solver function was used to minimize the RMSE, however, the results were highly controlled by the initial settings of the six values, and therefore calibration was conducted by visually comparing the modeled and observed flow duration curves. The final reservoir release and volume thresholds (as shown in **Figure 5-8** and **Equation 5-5**) resulted in relatively well replicated annual flow duration curves (**Figure 5-9**, RMSE = 41.7 cms), which were considered acceptable for this analysis. The Nash Sutcliffe Efficiency computed between the modeled and observed annual flow duration curves, however, does suggest there is still room for improvement in reservoir operating rules in the future (NSE= -0.47).

Although the flow duration curves are well replicated by the operating rules, daily streamflow values and the historic volume of Betania, were not well replicated by the operating rules (**Figure 5-10**). Volume is likely not well replicated because, although the overall trends in streamflow are captured by the modeled operating rules, each daily decision in releases is not well replicated. Because the model keeps the reservoir less full than historically, power generation estimations were underestimated by the WEAP model. Historically, Betania generated on average 2.25 billion Kilowatt hours per year between 2003 and 2010 (XM, n.d.), and the operating rules used here resulted in 1.76 billion kilowatt hours. . For the purposes of this study, where the performance measure is the difference between the regulated flow duration curve and the reference, these operating rules perform sufficiently well (**Figure 5-9**). However, because the modeled energy generation underestimated historical records, and was not considered in the calibration of reservoir operations, the energy calculated from WEAP was not used in this analysis to compare tradeoffs between development plans. Instead, the size of the plants, in megawatts, is used throughout the analysis.

Once the thresholds for the operating rules were determined for Betania, I applied the same volume thresholds and rules to the other reservoirs, with some minor variations. I divided all reservoirs except Guarapo, Oporapa and Chillurco into the four threshold volumes (**Figure 5-8**). Guarapo, Oporapa and Chillurco are divided only into the Max operating zone, buffer zone and inactive zone because 43% of their total volume is less than the defined inactive zone (**Table 5-2**). These reservoirs only operate based on the first and third rules (**Equation 5-5**).

Within WEAP, reservoir releases are controlled by flow requirement nodes downstream of each reservoir (**Figure 5-2**). The flow requirement is calculated based on **Equation 5-5**, based on the reservoir volume from the previous time step. The flow requirement demands water from the reservoir, controlling its releases. WEAP uses a priority scheme to allocate water to different demands. Demands with the highest priority receive water first, and demands with lower priorities only receive water if it is available once the higher priority demands have been met. Within this model, the flow requirements have a higher priority than the reservoir upstream of them, which have a higher priority than the next downstream flow requirement. This ensures that the most upstream flow requirement (reservoir release) is satisfied first, then the corresponding reservoir is filled if additional water is available, and then the next downstream flow requirement is satisfied by releases from the reservoir directly upstream of it (which receives water from the reservoir releases upstream of it), and its corresponding reservoir is filled, etc. This arrangement ensures that there is no coordination between the reservoirs, or, an upstream reservoir will not send water purposefully in order to meet the flow requirement associated with a downstream reservoir, but will only release enough water to meet its flow requirement. This mimics the actual Colombian energy market and reservoir operations, which are not coordinated between upstream and downstream reservoirs.

Equation 5-5

If Vol_{t-1} *is within the* ***Max Operating Zone****, then*

$$Q_{out,t} = Q_{Max} * R_{Max}$$

If Vol_{t-1} *is within the* ***Target Zone****, then*

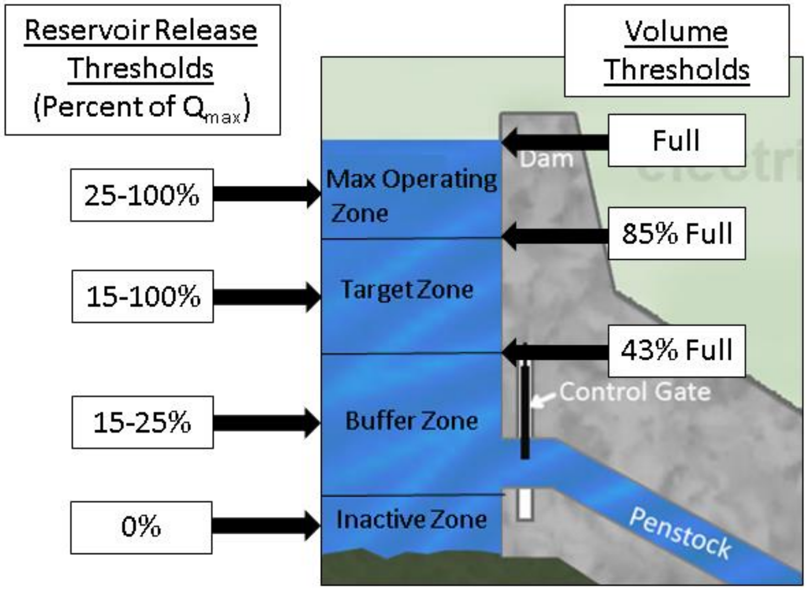
$$Q_{out,t} = Q_{Max} * R_{Targ}$$

If Vol_{t-1} *is within the* ***Buffer Zone****, then*

$$Q_{out,t} = Q_{Max} * R_{Buff}$$

If Vol_{t-1} *is within the* ***Inactive Zone****, then*

$$Q_{out,t} = 0$$



Where
Vol_{t-1}*=Volume of the reservoir at the previous timestep*
$Qout_t$*= Release from the reservoir at the current timestep (cms)*
Q_{max}*= Max turbine capacity (cms)*
R_{Max} *= a uniformly distributed random number between 0.25 and 1*
R_{Targ} *= a uniformly distributed random number between 0.15 and 1*
R_{Buff} *is a uniformly distributed random number between 0.15 and 0.25*

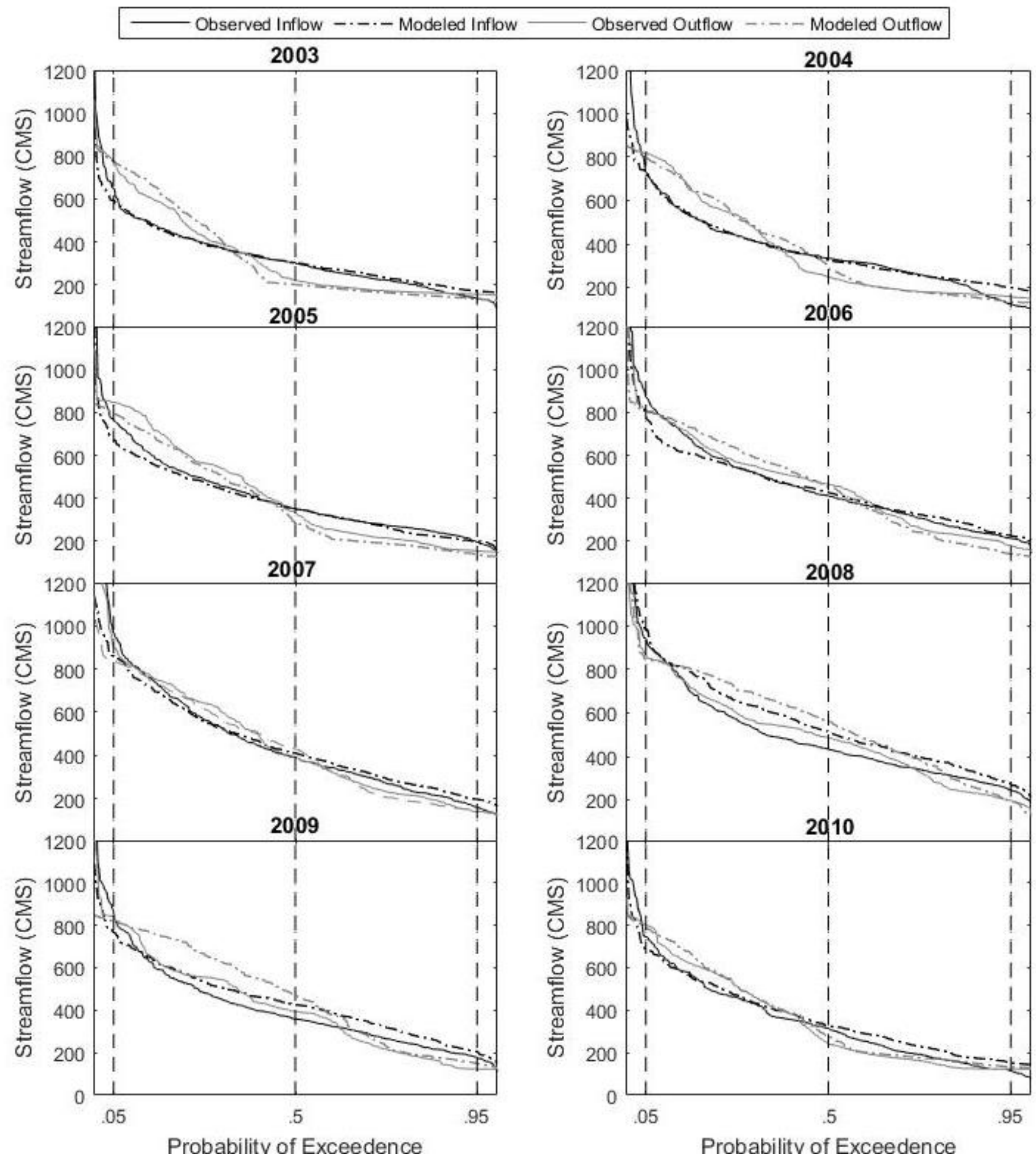


Figure 5-9. *Flow duration curves of observed and modeled inflows and outflows from Betania in 2003-2010.*

Observed flow duration curves were developed from mass balance calculations from raw daily storage and outflow data retrieved from XM, (n.d)

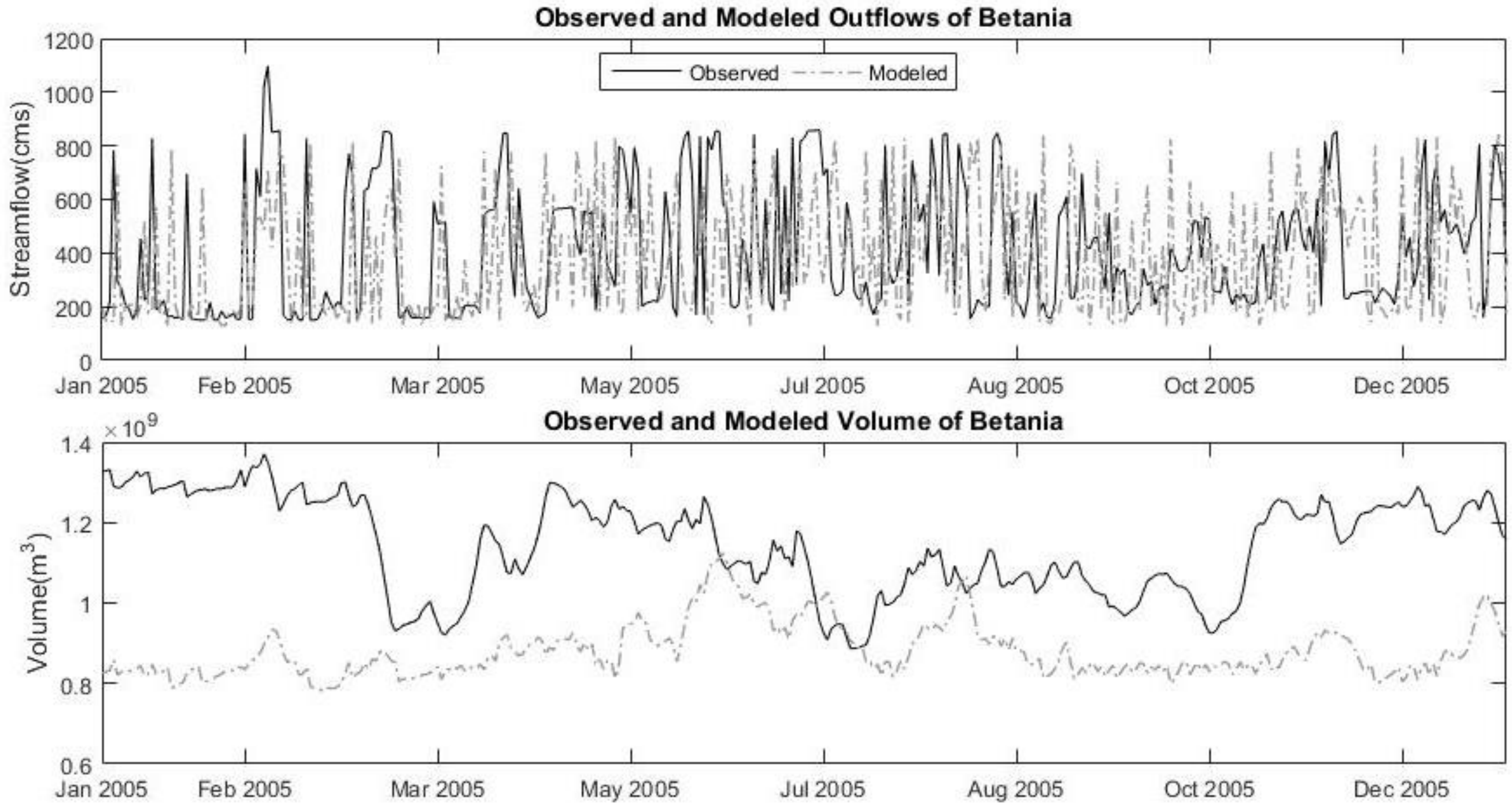


Figure 5-10. *An example on one year of modeled and observed streamflow and reservoir volume for Betania.*

Observed daily inflow and storage data were made available by XM (n.d)

5.3.2 Tributary Streamflow records and small hydropower projects

Historical records from the closest streamflow gauges to PCHs (**Figure 5-3**) were the main source of data for constructing PCH inflow records. Because of the hydrology and climatology of the area, where isolated thunderstorms dominate the high flows in these small tributaries, not many streamflow gauge records within the basin were well correlated with the gauges nearest to the PCHs. For this reason, the method of filling in gaps with streamflow gauges using only regression could not be used. To resolve this, a linear regression between each gauge of interest (gauge closest to a PCH) and every other gauge within the Alto Magdalena basin was developed. The linear regression with gauges 2109707 and 2113705, the two gauges whose records were largely impaired by Betania, were disregarded. The regression with the highest correlation was used to fill gaps in the record of the gauge of interest. Next, from the time series of residuals resulting from the regression, the variance of each year of residuals was calculated. Among only the time series of the residuals that had a complete year of values, the year of residuals with the median variance was saved. Where gaps occurred in the record of the gauge of interest, the regression was used to predict the missing daily streamflow values, and, if the r squared value of the regression was less than 0.5 (as was the case for all but one regression, **Table 5-1**), from the saved year of residuals, the series of residuals from the concurrent period of record which is being filled (same Julian day) was added to the calculated stream flows.

The goal of this methodology is to use the regression to maintain large scale trends in flows such as El Niño or La Niña years, and to use the residuals to add the variability of the small tributaries back to the record once it is transferred based on the regression. Any negative streamflow values resulting from this methodology were set equal to the minimum streamflow from the raw gauge data. If gaps still remained in the record, this methodology was repeated with the next best correlated gauge, until all gaps in the record were filled (**Table 5-1**). The flow records and flow duration curves for these tributary gauges before and after flows were filled in are shown in the Appendix. A comparison between the mean, standard deviation and coefficient of variation (Cv) between the raw gauge data and the filled in records suggests that with this methodology, the overall mean and variability were maintained in the filled in flow records (**Table 5-3**).

Once all historical records were complete for 1972-2010, they were scaled for the location of each PCH using **Equation 5-6**. For all PCHs except Socorro, inflow is equal to the complete scaled historical record of stream flows at the location of the project because there are no other projects nor inflows upstream of PCHs (**Figure 5-2**). Because of this, Socorro is the only project's streamflow record which required adjustment using **Equation 5-3**. The inflow at Socorro is the difference in flows between the scaled streamflow record at Santa Maria and at Socorro. No negative values resulted from this adjustment.

Equation 5-6

$$\frac{Q_{HP}}{A_{HP}} = \frac{Q_G}{A_G}$$

Where:

Q_{HP} *= Streamflow records at the location of the PCH*

A_{HP} = Drainage area upstream of the PCH
Q_G = Streamflow records from the gauge
A_G = Drainage area upstream of the gauge

Although the tributaries where the PCHs are located flow into the Magdalena River (**Figure 5-3**), they are handled separately in the WEAP model (**Figure 5-2**). Because the method used to fill gaps in the records of these tributaries, and some gauges located on tributaries were scaled up significantly to represent streamflow in larger rivers downstream, and although these filled records preserved the long term average and variability of the raw data, they may contain significant error on the daily time step. As to not introduce this error to the mainstem projects, because the water that these tributaries contribute to the river has already been accounted for by drainage area scaling, and because these small projects only have very local effects in changes to streamflow, the modeled flow of these tributaries is not added to the mainstem of the Magdalena River within the WEAP model. These tributaries are still included, however, so that their energy generation can be included in the basin wide energy demands and so that their local impacts can be compared with the large projects in the future.

Although these streamflow records and small projects are included in the WEAP model, they were not simulated in this analysis. Because the hydropower operations of Betania did not well replicate the volume of the reservoir, and therefore the energy generation, the energy generated by projects in the model was not included in the analysis. Improvement of reservoir operations which replicate historical energy generation would allow this model to be used to assess basin wide energy generation among both small and large hydropower projects in the future.

	Statistics from Observations			Statistics from Filled Record		
Gauge of interest	**Mean**	**St Dev**	**Cv**	**Mean**	**St Dev**	**Cv**
2114705	17.4	19.8	1.1	16.6	17.0	1.0
2114701	75.8	59.5	0.8	75.6	59.4	0.8
2111708	7.8	4.2	0.5	7.8	4.2	0.5
2110702	4.9	2.9	0.6	4.8	2.7	0.6
2112702	15.1	9.9	0.7	15.5	10.9	0.7

Table 5-3. *Statistics of daily streamflows representing observations from tributary gauges and filled in records.*

5.3.3 Measuring changes in streamflow

The non-inferior set of reservoir combinations were run in WEAP for 1972-2010. Betania and El Quimbo were both in operation in every scenario as well as the reservoirs for the combination run. A median annual flow duration curve was developed for each year between 1973 and 2009 (the first year was eliminated to remove the effects of filling the reservoirs) for each scenario at three points: downstream of Perícongo, downstream of Betania and downstream of Basilias (**Figure 3-1**). The same was done for the reference scenario, which did not have any active reservoirs. The percent difference between the median scenario curve and the median reference curve (the basin without any reservoirs) at Q5, Q50 and Q95 was calculated to capture the high, median and low flows. Efficiency for each scenario was calculated as the ratio of megawatts gained to the absolute value of the sum of the percentage change in streamflow in the reach downstream of Perícongo and Basilias.

Chapter 6 Results

6.1 Connectivity analysis

On a tradeoff curve between megawatts gained and connectivity lost in river kilometers, among the 256 total combinations of projects analyzed, there are 15 non-inferior combinations, or, said differently, there are 15 plausible 'near optimal' development scenarios (**Figure 6-1**, **Table 6-1**). This means that there are no other scenarios, of those considered, that generate the same amount of power with less connectivity lost than these 15. The non-inferior set can be ordered in three development paths, "aa", "ba", and "ac" (**Figure 6-2**). Based on connectivity, it is never better to develop downstream of El Manso than upstream (**Figure 6-1**, **Figure 6-2**).

When scenarios among each set of development alternatives are compared, there are additional scenarios in each respective non-inferior set. Across only combinations of two projects, there are three in the non-inferior set, but only two of them are included in the overall non-inferior set because this additional two project combination is superseded by a three project combination which has greater megawatts gained and less connectivity lost (**Figure 6-1**). This occurs with one, five, and six reservoir development scenarios as well.

Along the line of non-inferior sets, of particular interest corresponds to building one reservoir, El Manso, which results in significant generation capacity gained, but relatively little connectivity lost (**Figure 6-1**, **Table 6-1**). This reservoir is the most efficient reservoir considered in terms of megawatts gained per kilometer of connected river lost when compared with all other project combinations and all other individual projects (**Figure 6-3**, **Figure 6-2**). However, if two reservoirs are built, much more connectivity is lost for each megawatt gained, and efficiency decreases greatly (**Figure 6-1**, **Figure 6-3**a). There is a stretch of optimal project combinations which result in substantial megawatts gained but do not sacrifice significant connectivity (scenarios 2a and b, 3a and b, 4a and b and 5a, **Figure 6-1**). Because of this, efficiency increases across these scenarios, from less to more development (**Figure 6-3**a). These project combinations consist of developing upstream and developing El Manso (**Table 6-1**, **Figure 6-2**). Once development moves downstream (Scenarios 5c and 6a), each additional project contributes much less power generating capacity for the amount of connectivity lost (**Figure 6-1**), and therefore the efficiency drops as well (**Figure 6-3**a, **Table 6-1**). From less to more development across these later projects (5c to full development), megawatts gained is proportional to connectivity lost, and therefore the efficiency does not vary greatly between 5c and full development (**Figure 6-3**a).

Individually, El Manso is the most efficient project, with the highest ratio of megawatts gained to connectivity lost (**Figure 6-3**b, **Table 6-1**), equal to 7.6 megawatts per kilometer disconnected. The next project with significantly high efficiency is Venado, a proposed PCH (**Figure 6-3**b). After these two projects, there is a large gap in efficiency, where all other individual projects gain less than one megawatt per kilometer lost (**Figure 6-3**b). In general, the PCHs are less efficient than the large projects in terms of connectivity (**Figure 6-3**b).

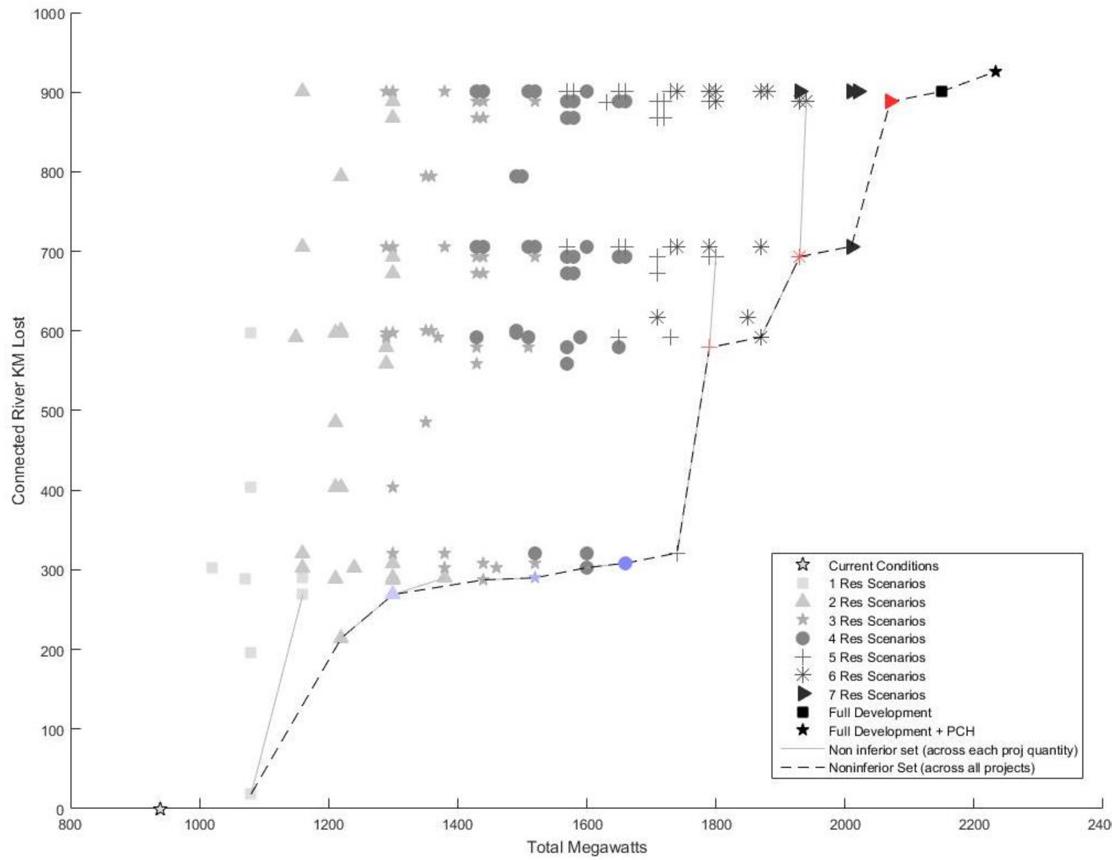


Figure 6-1. *Tradeoff curve between megawatts gained and river kilometers lost for every combination of large hydropower projects, and full development of large project with full development of PCHs.*

Each point represents a combination of projects. "b" scenarios are shown in blue and "c" scenarios are shown in red (Figure 6-2).

Non-inferior Set:			
Combination Code	**Project Names**	**Total MW**	**River km lost**
1	El Manso	1080	18
2a	Guarapo, El Manso	1220	215
2b	Guarapo, Chillurco	1300	269
3a	Guarapo, Chillurco, El Manso	1440	287
3b	Guarapo, Chillurco, Oporapa	1520	290
4a	Guarapo, Chillurco, Oporapa, El Manso	1660	308
4b	Guarapo, Chillurco, Oporapa, Perícongo	1600	303
5a	Guarapo, Chillurico, Oporapa, Perícongo, El Manso	1740	321
5c	Guarapo, Chillurco, Oporapa, El Manso, Veraguas	1790	579
6a	Guarapo, Chillurico, Oporapa, Perícongo, El Manso, Veraguas	1870	592
6c	Guarapo, Chillurco, El Manso, Veraguas, Bateas	1930	693
7a	Guarapo, Chillurico, Oporapa, Perícongo, El Manso, Veraguas, Bateas	2010	706
7c	Guarapo, Chillurico, Oporapa, El Manso, Veraguas, Bateas, Basilias	2070	888
Full Dev	Guarapo, Chillurico, Oporapa, Perícongo, El Manso, Veraguas, Bateas, Basilias	2150	901
Full Dev + PCH	Guarapo, Chillurico, Oporapa, Perícongo, El Manso, Veraguas, Bateas, Basilias + All PCHs	2233.7	926

Table 6-1. *Details of the non-inferior set of projects.*

Black text corresponds to the “a” development path, blue to the “ba” path and red to the “ac” path (see **Figure 6-2**).

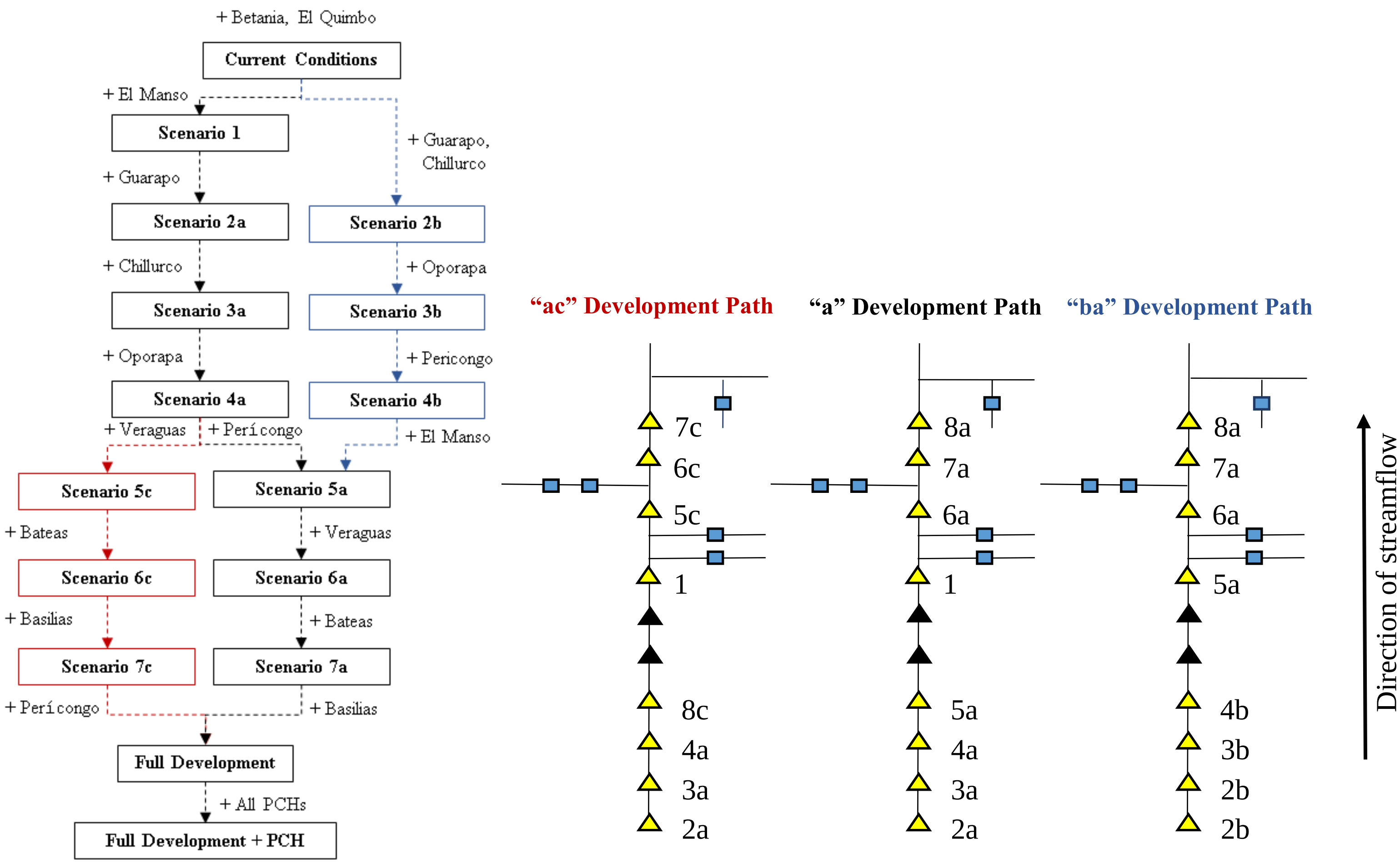


Figure 6-2. *Schematic of development paths through the scenarios included in the non-inferior set (a) and the order of the development of projects in the basin for each development path (b).*

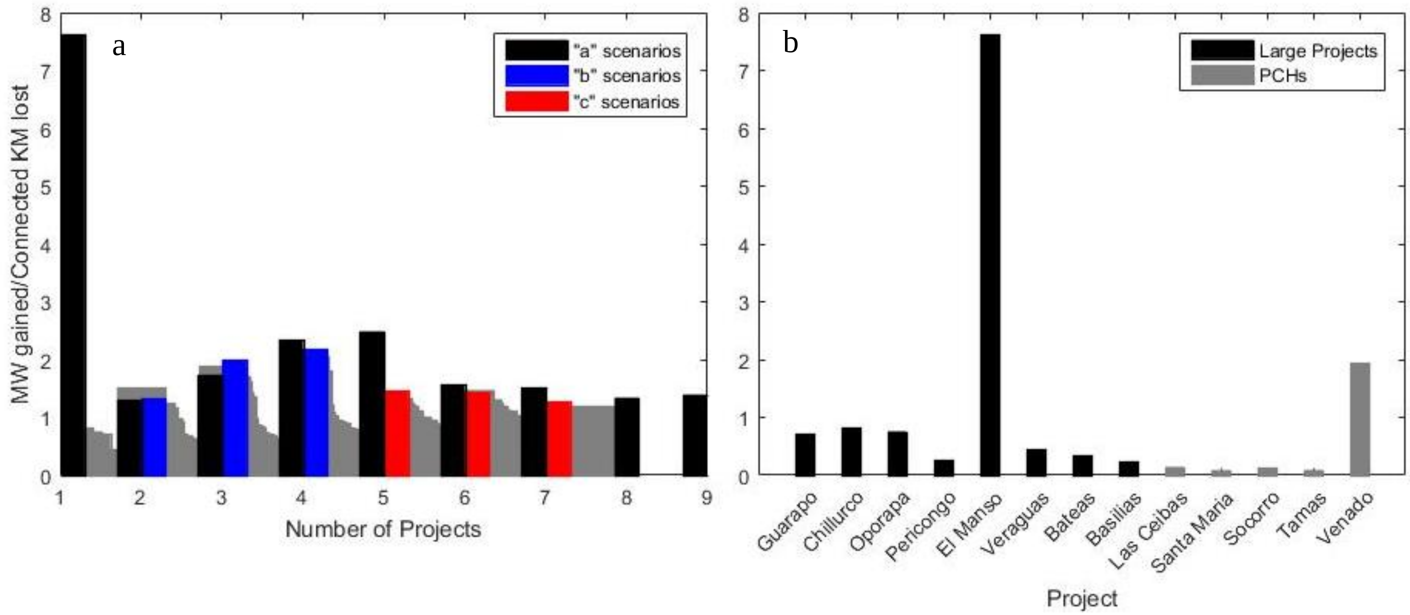


Figure 6-3. *Plot of efficiencies: megawatts gained for connected river km lost for all project combinations (a) and individual large projects and PCHs (b).* In figure a, the overall non-inferior set of project combinations is shown in black, blue and red, other project combinations are shown in gray.

6.2 Streamflow impacts

The overall non-inferior set of project combinations based on connectivity was run in the WEAP model, with each combination as its own scenario. When the median annual flow duration curve is plotted for each scenario, including the reference (no reservoirs) and current conditions (Betania and El Quimbo in operation), generally, a greater number of projects developed (darker colors) results in greater deviation from the reference curve (curve with no projects operating) (**Figure 6-4**, **Figure 6-7**). In the reach downstream of Betania, however, all of the scenario curves (all but reference) are very similar (**Figure 6-6**). Although the impacts of upstream development are significant in the reach downstream of Perícongo, upstream development does not appear to significantly impact streamflow downstream of Betania (**Figure 6-6**). There are exceedance probabilities on all three figures where the scenario curves cross the reference curve and have the exact same value (**Figure 6-4**, **Figure 6-6**, **Figure 6-7**). In the reaches downstream of Perícongo and Basilias, this crossing point varies between scenarios so that at some exceedance probabilities (i.e., approximately 0.7), some development scenarios have a streamflow greater than the reference, and some less than the reference (**Figure 6-4**, **Figure 6-7**). The location of these points was not further investigated in this study, but is pointed out because selecting streamflows with different probabilities of exceedance than were selected here, such as 0.7, may provide very different results in impacts.

6.2.1 Impacts upstream

Figure 6-5 and **Figure 6-8** show a more detailed picture of the changes occurring to three specific values on the flow duration curve: flows with an exceedance probability of 0.05, 0.5, and 0.95 in the reach downstream of Perícongo and Basilias, respectively. In the reach downstream of Perícongo, the median flow duration curve is not impacted by the development of El Manso (Scenario 1), because it is located downstream (**Figure 6-5**). With this development scenario, megawatts are gained with no impacts to streamflow at this point. Once development moves upstream (Scenario 2a-5a, 2b-4b), high and low flows decrease sharply, and median flows increase sharply (**Figure 6-5**). There are large changes to the streamflow regime for only small gains in megawatts. Once scenario 4b (for the "ba" development path), 5a (for the "a" development path) and 4a (for the "ac" development path) are reached, impacts do not significantly change, until the last reservoir, Perícongo, in the "ac" development path is added (**Figure 6-2**, **Figure 6-5**). Again for these scenarios, megawatts are gained with almost no additional impacts to the streamflow regime. The maximum percent change to the Q5, Q50 and Q95 flows downstream of Perícongo are -16.4%, 21.8% and -30%, respectively.

There is a slight fluctuation between the later scenarios (4a to 7c along the "ac" development path and 5b to full development along the "ba" development path), which should not be differently impacted by additional downstream development (**Figure 6-5**). It is expected that the impacts in the reach downstream of Perícongo for each later scenario along the same development path would be exactly the same. Even still, these fluctuations are small, varying by less than 1% change in streamflow from the reference conditions, and therefore assumed negligible for this analysis, which is discussed further in section 7.2.1 (**Figure 6-5**).

6.2.2 Impacts downstream

Impacts to the Q5 Q50 and Q95 median annual flow duration curve from the reach downstream of Basilias generally show the opposite trend from the reach downstream of Perícongo, as development paths progress. In the early scenarios along the development paths where development mainly occurs upstream, impacts to the median annual flow duration curve downstream of Basilias are much less than when development moves downstream (scenarios 4a and 4b, to full development, **Figure 6-8**). This is to say that upstream development results in little disruption to the streamflow regime at this point, below Basilias, with large gains in power generating capacity. The maximum percent change in the median flow duration curve downstream from Basilias of Q5, Q50 and Q95 flows is -12.8%, 16.4%, and -46%, respectively and the maximum incremental percent change (beyond current conditions), is -8.5%, 14.8% and -22.0%, respectively.

At this point, because the reach downstream of Basilias is the most downstream reach in the study area, it is expected that all development scenarios will affect the flow duration curve. However, the fluctuations between points that are not expected to change greatly (progression from scenarios 1 to 4a, for example), do fluctuate between greater to less deviation from the reference, such that more development does not always mean greater impacts to the flow duration curve (**Figure 6-8**). These fluctuations are greater than what was seen in the reach downstream of Perícongo, but still relatively small, less than 2% change in streamflow from the reference, and therefore, are again considered negligible for this analysis (**Figure 6-8**, see section 7.2 for further explanation of these fluctuations).

6.2.3 Efficiency

When the impacts to the reaches downstream of Perícongo and Basilias are combined, and divided by megawatts gained for each scenario, the overall efficiency of the development scenarios can be compared. For high flows (Q5), efficiency is steadily gained as development increases, or, the added power generating capacity for the progression between each scenario is consistently greater than the incremental streamflow impacts to high flows (**Figure 6-9**). For both the median and low flows, efficiency increases during earlier, or upstream development, but stays generally steady across later, downstream development (**Figure 6-9**). When development moves downstream, the added power generating capacity between each scenario is generally proportional to the incremental impacts to streamflow. Between full development and full development with PCHs, efficiency increases as in this analysis, since the PCHs are assumed to have negligible downstream impacts (**Figure 6-9**). At all three points on the flow duration curve, full development with PCHs is the most efficient development scenario (**Figure 6-9**).

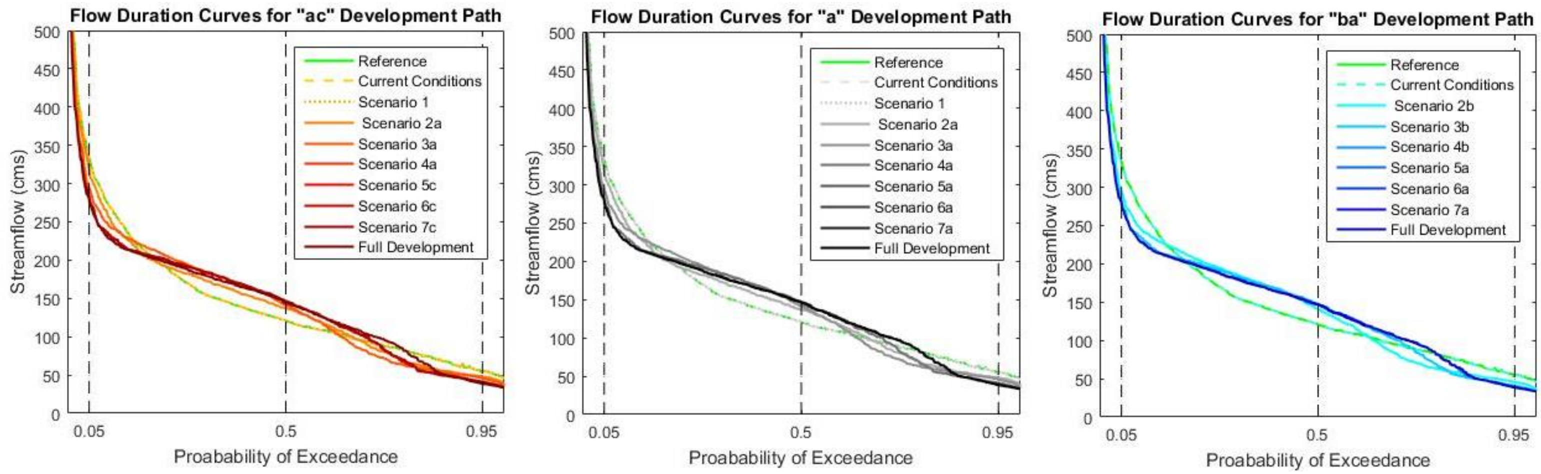


Figure 6-4. *Median flow duration curves for the reach downstream of Perícongo for each scenario along the three development paths.*

"Reference" is the basin without reservoirs, "Current Conditions" is the basin with Betania and El Quimbo in operation.

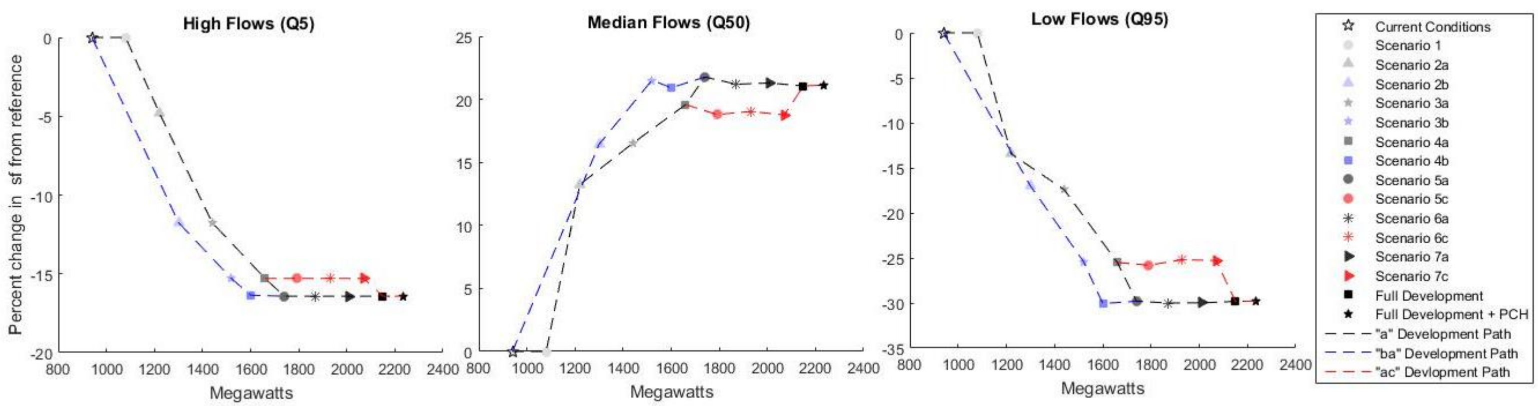


Figure 6-5. *Plot of the percent change in high, median and flow flows in the reach downstream of Perícongo for each scenario from the reference (basin without dams).*

Values are calculated as the difference between the median annual flow duration curves (**Figure 6-4**).

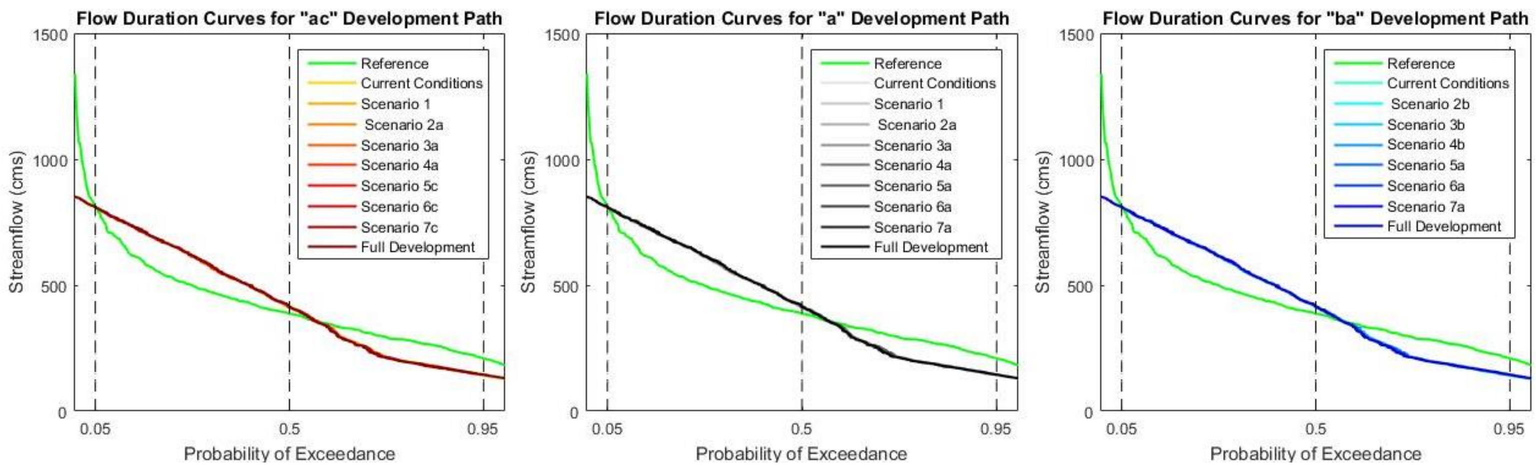


Figure 6-6. *Median flow duration curves for the reach downstream of Betania for each scenario along the three development paths.* "Reference" is the basin without reservoirs, "Current Conditions" is the basin with Betania and El Quimbo in operation.

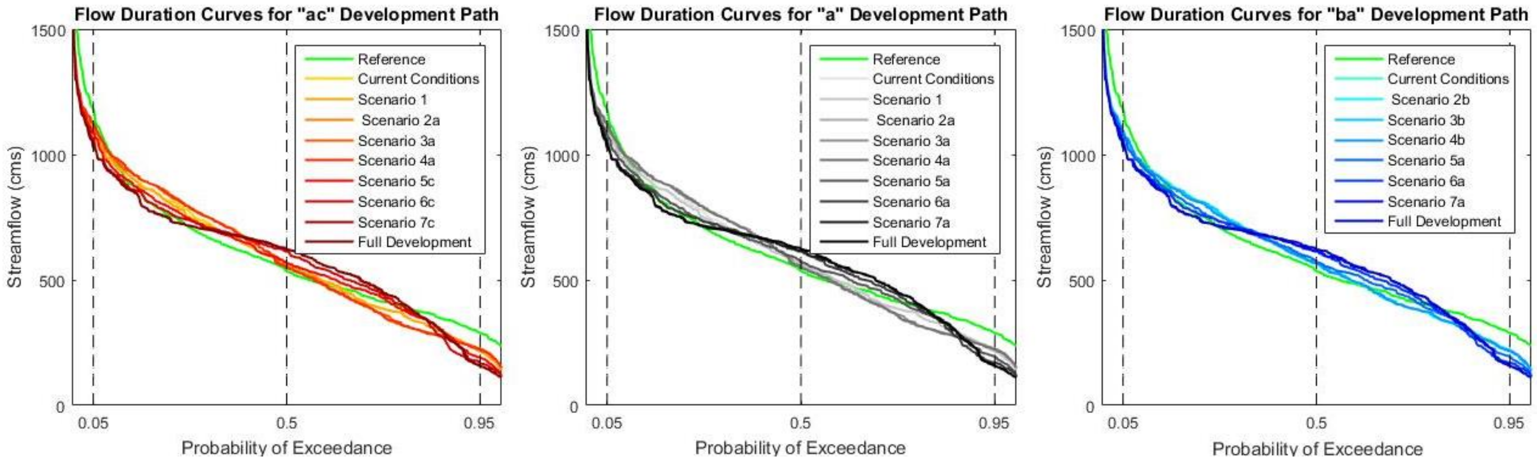


Figure 6-7. *Median flow duration curves for the reach downstream of Basilias for each scenario along the three development paths.*

"Reference" is the basin without reservoirs, "Current Conditions" is the basin with Betania and El Quimbo in operation.

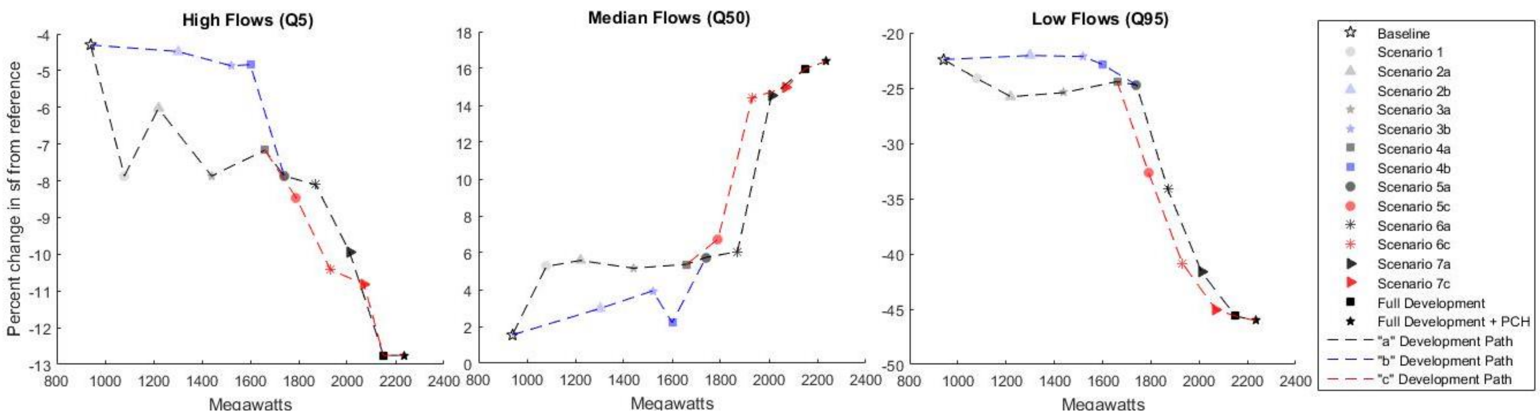


Figure 6-8. *Plot of the percent change in high, median and low flows in the reach downstream of Basilias for each scenario from the reference (basin without dams).*

Values are calculated as the difference between the median flow duration curves (**Figure 6-7**).

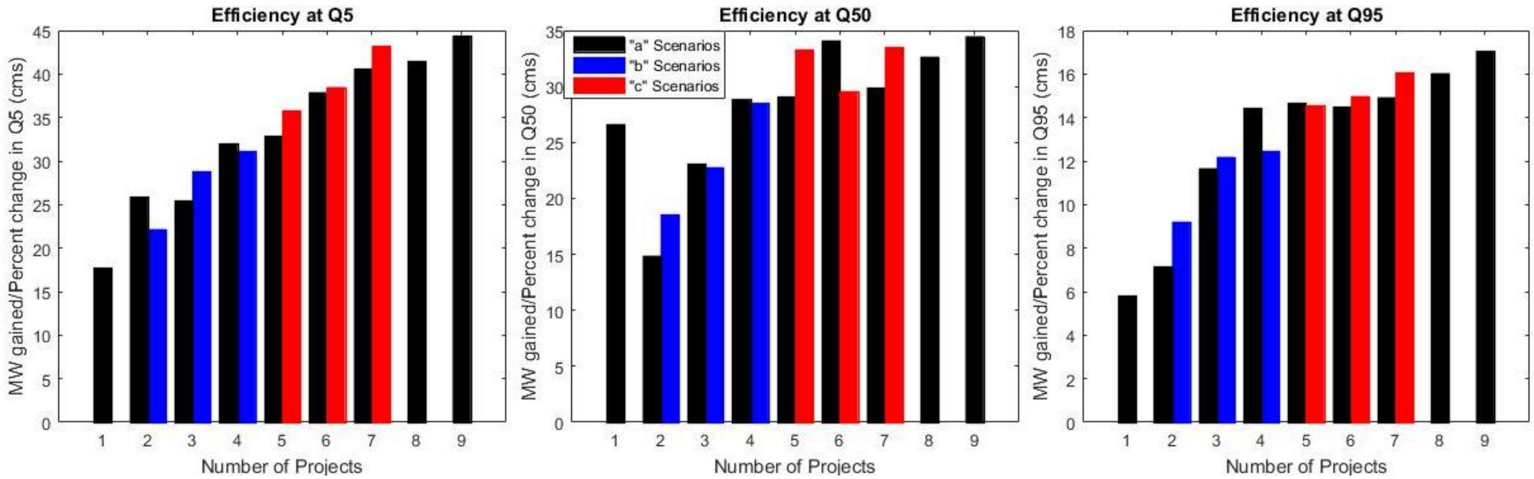


Figure 6-9. *Plot of efficiencies of megawatts gained to total streamflow change for all project combinations.* Total streamflow change is the sum of percent change in the reach downstream of Perícongo and Basilias.

Chapter 7 Discussion

This study aims to contribute to the decision making process by evaluating proposed hydropower plans in terms of a few basic indicators of the environmental impacts and expected power generation. The basic indicators of ecological function explored here provide a first look at tradeoffs between power and the environment. It is important to note, however, that additional study is needed to more adequately understand how changes to flow, river connectivity, water quality and project implementation may impact the various species living in the river, fish and others. Some of these additional considerations are discussed below.

7.1 Connectivity

7.1.1 Defining the non-inferior set and development paths

In this analysis, connectivity was assessed first because once a dam is built, its location cannot be changed. Reservoir operations and the resulting impacts to streamflow are much more flexible, once the reservoir is constructed. Optimal development options for minimizing connectivity lost while maximizing megawatts gained vary depending on the approach to development. If only two projects are built, it is important to assess the tradeoffs between only the two project combinations. The two project combination with the highest efficiency (**Figure 6-3**) falls just outside the overall non-inferior set because it is inferior to a three project combination which generates more power with less connectivity lost (**Figure 6-1**). Although building the combination of three projects provides more megawatts for fewer river kilometers disconnected, building a third project requires significantly more resources and has other impacts compared to building only two projects. The non-inferior set changes based on the development goal and therefore good development options could be missed if only the overall non-inferior set is considered.

These development paths are particularly interesting when considering how the implementation of certain strategies of development may affect decisions long term. If only some projects are built now, but additional projects will be built in the future, the most efficient or optimal initial decision may not result in optimal development in the long term. For example, if two projects are built now, and two more in the future, and the goal is to minimize river kilometers disconnected, or maximize efficiency, the initial decision might be to build project combination 2a (**Table 6-1**, **Figure 6-3**). However, the best four project combination for both of these objectives is 4b (**Table 6-1**, **Figure 6-3**). Because both projects built in scenario 2a are not included in scenario 4b, making the best decision to minimize connectivity lost and maximize efficiency early, results in a scenario that has greater connectivity lost compared to other scenarios later.

Another example may be if decision makers decide to build one reservoir at a time, but maximize power generating capacity with each new reservoir added, initially, the decisions would result in following the “ba” development path (**Table 6-1**, **Figure 6-2**)**Figure 6-3**. Later, however the “ac” development path results in greater megawatts, but because of early decisions made, specifically, to build Perícongo, the combinations along the “ac” development path cannot be built (**Table 6-1**, **Figure 6-2**). Another strategy may be to build the most efficient project at each step of development. This would mean the projects would be built in the order of El Manso, Chillurco, Oporapa, Guarapo, Veraguas, Bateas, Perícongo, and Basilias (**Figure 6-3**). In this order, when the first five projects are built, this is the same combination of projects as the 5c scenario (**Table 6-1**), which overall, is significantly less efficient than the 5a scenario (**Figure 6-3**). This is because the reservoirs are in series, so once one reservoir is built, the efficiency of adding an additional reservoir is different than if no reservoirs were built, or the efficiency of each project individually. This is another example of how important the overall non-inferior set and specifically, development paths are to consider, because decisions made early greatly affect later decisions.

7.1.2 Upstream vs downstream development

Based strictly on the non-inferior set, and therefore the projects that have the least connectivity lost and greatest megawatts gained, it is optimal to concentrate development upstream before downstream (**Figure 6-2**). This is because of the large gap and large tributary between El Manso and Veraguas (**Figure 3-1**). It only becomes optimal to develop downstream of El Manso once Veraguas is built, and because building Veraguas results in a large quantity of disconnected river kilometers, it makes sense to preferentially develop the upstream reservoirs to preserve a greater length of connected river.

There is evidence that there are fish populations both upstream and downstream which rely on the remaining connectivity of these systems to survive. The upstream populations may be smaller or less diverse, but also have a greater percentage of endemic species (Jimenez-Segura et al., 2014). The area of the basin and connected river kilometers available for migration upstream of El Quimbo compared to downstream of Betania is already much smaller under current conditions (**Figure 1-1**). Developing all four reservoirs upstream may result in overall less connectivity lost, but may also result in completely losing these fish populations if the river remaining is not sufficient to support their migration patterns. Additionally, as previously discussed, this area is sensitive because of how pristine some areas are, and because the ecosystems and biodiversity are still not well understood yet it is known that the area is rich in endemic and threatened species (Northern South America, n.d.; Forero-Medina & Joppa, 2010). Apart from just fish, upstream development could affect other important and potentially already stressed species. The downstream fish populations may have greater space available, but it is also difficult to determine how many connected river kilometers are sufficient to support these populations.

7.1.3 Large vs small hydropower

Although the PCHs are not highly efficient in megawatts gained per river kilometer disconnected (**Figure 6-3**), some projects may be located in areas too far upstream for migrating fish to reach (potentially Venado, Las Ceibas, Tamas, **Figure 3-1**, Jiménez-Segura et al., 2014). Others may be located in tributaries that would be essential to maintain if reservoirs are built upstream on the mainstem, as was the case in La Miel River (potentially Socorro and Santa Maria, Jiménez-Segura et al., 2014). Because of this, it is important to assess not just the number of connected river kilometers lost, but also the context in which the river becomes disconnected. It seems clear that species need a balance and variety of different types of ecosystems in order to carry out their migration patterns, and therefore, complete development of PCHs or complete development of large projects may disrupt migration patterns. At the same time though, certain combinations of large and small projects may also disrupt migration.

Although there is great potential for small hydropower within Colombia (Morales et al., 2015), and they have potentially fewer impacts than large projects, because the plants are significantly smaller in capacity than large plants, it would take many to meet the same energy expansion plans if they were to replace large projects. In terms of connectivity, because this analysis assumes complete obstruction resulting from small projects, it does not seem feasible to replace large projects with a sufficient quantity of small ones to meet the same energy generating capacity, especially considering the importance of conserving the remote areas in the upper portion of the basin (Northern South America, n.d.; Forero-Medina & Joppa, 2010; CAM, 2015). It should be further investigated, however, to determine if some or any large projects could be replaced by small projects and how the impacts of one large project compares to the cumulative impacts of many small projects.

Given the current government structure in Colombia, where CARs license small projects and the national government licenses large projects, and CARs are not required to consult with the national government in the process of licensing small projects, the impacts of the two project types are not assessed together to evaluate their integrated impacts and benefits. For this reason, under current conditions, considerations for fish migration patterns cannot be included holistically in development plans, and may result in fragmentation that could be avoided with collaboration between regional and national government entities. Additionally, there is no means to assess or carry out plans for replacing a large project with multiple small projects. While every combination of small and large project development was not considered in this analysis, nor the location of every small project relative to known species migration patterns, this study provides information that may allow for these types of considerations to be discussed by stakeholders and experts who best understand the needs of the species and the goals of the basin's development. This study also suggests the importance of participatory decision making and cooperation among government entities in order to maintain connectivity in ways that protect fish migration patterns and other important ecological functions, by demonstrating that small and large hydropower projects can amplify impacts to connectivity if not assessed together.

7.1.4 Biases of this analysis

There are inherent biases in this analysis because of the limited number of proposed projects included. In this analysis, all large projects are located on the mainstem and all small projects are on the tributaries. There are additional plans for development which include large projects on the tributaries (Angarita et al., 2015). The tradeoffs for these projects may look significantly different from those presented here because they may result in significantly less fragmentation, similar to the PCHs, but may result in significantly more hydropower generating capacity. There may be development options which include these projects and perform significantly better in terms of maintaining connectivity and gaining power generating capacity than those presented here. The same concern exists for these projects as was noted previously, that the combination of tributary and mainstem projects may result in disruption of essential pathways migrating species may need if one development occurs in one area as opposed to another. Differently however, because these projects are all large, their impacts may be assessed together by the ANLA.

Additional biases come from the project combinations that were not assessed here, among different PCHs and large projects, as well as the PCHs that have already requested licenses from the CAM but whose location data was not available at the time of this analysis and therefore they were not included. Because every combination of all projects were not included, there may potentially be combinations of the two project sizes that may perform better than others. These development options are missed by this analysis and should be further investigated.

7.2 Streamflow impacts

7.2.1 Upstream vs downstream development

Based on connectivity, development of El Manso and reservoirs upstream of El Quimbo provide some highly efficient development options which to do not sacrifice significantly more connected river kilometers than current conditions, but do provide significant gains in megawatts (**Figure 6-1**, **Figure 6-3**). However, streamflow impacts resulting from upstream development do affect the remaining connected section of the river between the most downstream proposed dam and El Quimbo. Even if fish populations are able to inhabit this area given the amount of connectivity remaining once the upstream reservoirs are developed, they may not be able to carry out their migration patterns with impaired streamflow.

Impacts downstream of Perícongo are significant with upstream development but there are little to no impacts during downstream development. Additionally, impacts to development upstream of Perícongo do not largely affect impacts to streamflow downstream of Betania or Basilias. The flow duration curve downstream of already constructed Betania will remain impaired despite upstream development. This is likely due to the large size of Betania and El Quimbo, which are significantly larger than any of the proposed upstream reservoirs (**Table 5-2**), and their location relative to the upstream proposed projects (**Figure 3-1**). Because these reservoirs are located so far downstream from the upstream reservoirs, and there is a significantly large tributary just downstream of El Quimbo (**Figure 3-1**), small fluctuations in daily inflows resulting from upstream reservoirs do not significantly change the way Betania and El Quimbo will operate, and therefore do not have a large impact on the flow duration curve downstream of Betania. Because upstream development does not impact flows downstream more so than the current operations of Betania and El Quimbo, upstream development may be tolerated by existing downstream fish populations or the rest of the ecosystem including other species which rely either on fish populations or also on the varying flows of the river.

The maximum percent change to all three measured stream flows in the reach downstream of Perícongo are greater than the maximum incremental percent change to those below Basilias (**Figure 6-5**, **Figure 6-8**). This may be because streamflow downstream of Basilias is much greater overall due to tributaries and contributing groundwater. The additional water relative to the small size of the downstream operating volumes may mitigate the reservoirs' impacts at this point. Although they may be incrementally less than upstream, the streamflow impacts downstream of Basilias extend through the rest of the basin (**Figure 3-1**), and therefore may affect a larger population of fish than upstream impacts.

The fluctuations between some scenarios that were unexpected, for example between later development scenarios in the measurements downstream of Perícongo, and earlier development scenarios in the measurements downstream of Basilias (**Figure 6-5**, **Figure 6-8**), were investigated more thoroughly with the developer of WEAP. On some days of the scenario, WEAP allocates slightly different volumes of water to the same flow requirements between scenarios, even though the value of the flow requirement for that time step did not vary between scenarios, and priorities are such that water is only allocated to one flow requirement or one reservoir at a time. For example, the flow requirement downstream of Guarapo is the first requirement to be filled despite the scenario. The daily sequence of flow requirement values, which demand water from the Guarapo reservoir is the same between scenarios 5a and 6a, which both include Guarapo in operation (**Figure 6-2**). However, the daily sequence of stream flows out of the reservoir, therefore the allocation of water from the reservoir to the flow requirement, are slightly different. The differences between the allocations on each day between the scenarios is less than 1cms. In some cases, the differences are sufficient enough that the sequence of reservoir volumes between the two scenarios are also different, and occasionally this is enough that the volume of a reservoir sometimes falls within different operating zones between scenarios and therefore the flow requirement changes as well. The reason for these differences may be due to inconsistencies in rounding resulting from many iterations of the software (allocations calculated for each day over 37 years based on the volume of the previous day), but should be further investigated. These differences may compile enough to affect the median flow duration curves between scenarios and cause the fluctuations seen in **Figure 6-5** and **Figure 6-8**. The small variations may compile to be greater in the reach downstream of Basilias because the last flow requirement, and therefore the last allocation of water in each time step, is solved at this reach. Also, because the downstream reservoirs are smaller (**Table 5-2**), and therefore the difference between the threshold volumes are smaller, the small variations may affect the volumes and the flow requirements more so downstream than upstream.

Generally, the hydropower operations considered in this study result in decreasing high flows, increasing average flows and decreasing low flows (**Figure 6-4**, **Figure 6-6**, **Figure 6-7**) which replicates the impacts seen in the historical inflow and outflow data from Betania (**Figure 5-9**), but not necessarily reservoir operations commonly seen, as discussed in section 5.3.1.4. This approach is reasonable given the scope of this study, which aims to replicate "business as usual" operations given the available information. No operations were coordinated between projects which is also reasonable given the state of hydropower operations and the market in Colombia, where operators of large dams do not cooperate (see section 4.1.1). However, this may not be how the proposed, smaller reservoirs are operated because they may have different contracts and strategies. Additionally, energy generation and environmental conditions could likely be improved by coordinating reservoir operations between these in-series reservoirs. (Lund and Guzman, 1999; Lund, 2000; Shen et al., 2015; Ledec & Quintero, 2003). Additional improvements in operations might be possible by exploiting a difference in regional hydrology in the Alto Magdalena River basin where upstream reservoirs receive inflow due to additional precipitation generated by the influence of the Amazon system during periods of the year when downstream reservoirs do not (see section 4.3).

Alternate reservoir operations were not assessed in this analysis, but could present important opportunities in the tradeoffs between reservoir operations and impacts to streamflow. Reservoir operations could better cooperate and generate more energy, shifting the tradeoff curves. In this case, it would be important to evaluate power generated from different development scenarios, rather than just their size, as was done here. Contrarily, the operators could adopt more environmentally conscious rules, or these could be included as operational requirements in the project licensing process. This may create a situation where, although connectivity is lost upstream of a reservoir, the fish populations downstream will still receive the correct flow signatures to carry out migration and reproduction. Implementing cooperative reservoir operations would require either significant changes to the energy market or to the considerations and regulations included in environmental licensing.

7.3 Repercussions of regional vs National decision making

Although not assessed in this analysis, the CAM has concern for water quality issues resulting from future development as well as people displaced and land lost to new reservoirs (WEAP Team, CAM, personal communication, January 20, 2016). The CAM has specific and important regional knowledge about the potential impacts of these proposed projects and what matters to the people and ecosystems in the area. Although the ANLA is obligated by law to include CARs in the licensing process, the lack of effective mechanisms to communicate between the two scales of government and limited time available to do so once a project requests a license may sometimes inhibit this cooperation from being successful in practice (for example, “El Quimbo”, 2016; Duarte-Abadía et al., 2015). Additionally, the implementation of projects may not always be carried out as the cooperative plans intended. Because the CARs are located in the area that is affected by projects, they are required to manage the impacted area whether or not they had an opportunity to be well represented in decisions regarding its development. This has been demonstrated with El Quimbo (“El Quimbo”, 2016), and in the Sogamoso River (Duarte-Abadía et al., 2015). With El Quimbo, although all or, at least, the majority of the biomass in what is now the El Quimbo reservoir was planned to be removed prior to filling the reservoir, this did not occur, resulting in low dissolved oxygen in the water and fish kills discussed previously (“El Quimbo”, 2016). In the case of the Sogamoso River, although the same laws apply in this basin requiring cooperation between regional and national entities, it is suggested that because national and international entities hold the majority of economic and political power, and may be corrupt, the local populations that were most severely impacted by the project’s development were not well considered, and these same populations did not see any of the benefits of the project that private, national or multinational organizations did (Duarte-Abadía et al., 2015). Similar with this situation, in the case of future development, the energy generated may not entirely serve Colombia, and is intended to be sold internationally (“The Republic”, 2013). Because of this, the people and area which suffers the damage and impacts may not directly benefit from them.

This study demonstrates that development scenarios among the proposed reservoirs have widespread impacts and it is clear that basin or nation-wide planning is needed. However, in order for nationwide planning to be successful, both regional and national stakeholders should be included in the decision making process so that the national goals of energy generation can be balanced with the regional effects of the decisions. While the government structure of Colombia may seem participatory on paper, the gap between the CARs and the national governments who ultimately make decisions regarding these large projects seems to hinder participation and inclusion in practice (Duarte-Abadía et al., 2015; “El Quimbo”, 2016).

Chapter 8 Conclusions and future work

This analysis demonstrates the tradeoffs between hydropower generating capacity and some environmental impacts resulting from various combinations of small and large hydropower projects and by doing so, introduces a generalized methodology for evaluating these tradeoffs. There are clear projects and project combinations which better preserve connectivity of the river system while still resulting in increases in power generating capacity. A systems approach was taken to evaluate a large number of alternative development plans for their ability to both generate hydropower and for their environmental impact. It is shown that selecting a non-inferior set of projects can only be done within the context of a large suite of development plans, or some well performing projects may easily be missed. Thus this study has shown the importance of a ‘systems’ approach to selecting development plans.

In terms of minimizing connectivity lost, it was shown for this basin that it is better to build upstream reservoirs than downstream, however, the impacts to streamflow upstream reaches, resulting from upstream development are greater than downstream development’s impacts to downstream flows. Although upstream consequences may affect a smaller population of fish, this population is largely endemic and still may migrate and these projects are located in ecologically sensitive areas. Impacts of upstream development to downstream flows are minor due to the influence of Betania. Impacts of downstream development on downstream flows, although less than the impacts of upstream development upstream, extend downstream through the rest of the Magdalena basin and therefore may impact a larger population of fish and a larger ecosystem.

A better understanding of daily reservoir operations would greatly contribute to this work so that reservoir volume, outflows, and energy can be modeled for these proposed and other projects. This analysis contributes to reservoir operation simulations in WEAP by simulating reservoir operations at the daily timestep, an approach that has not yet been well established in Colombia. While this analysis advances modeling techniques in WEAP, additional steps could be taken to further improve daily operating decisions. Some potential improvements to the approach here may be to further manipulate reservoir volume thresholds, and potentially set these values differently based on seasons throughout the year and whether or not the year is influenced by El Niño or La Niña. These approaches may allow reservoir volume to be better replicated by the model, and therefore energy generation as well. A better understanding of the sensitivity of the model to variations in the volume and reservoir release thresholds may allow for the variables to be better adjusted to replicate historical records. Other statistics of streamflow besides the annual flow duration curves should be compared between modeled and observed streamflows to better understand where the model does and does not perform well. Some statistics may include average annual and monthly flows, coefficient of variation, and flow duration curves for specific time periods of interest such as for only dry or wet periods of the year. The ability to replicate historical operating rules and energy generated would allow for different reservoir operating rules, including ones with consideration for environmental flow requirements and other considerations for ecological needs, to be compared with baseline conditions. Also, rules which allow and promote cooperation between reservoirs could be investigated. This would allow for the flexibility of the system, or the tradeoffs between energy generated and streamflow impacts between different operating rules, to be better understood and explained.

The performance measures included in this analysis are tied to knowledge of migrating fish populations and ecosystem services, however, are still quite general and likely do not capture every aspect of impacts that may be important for these considerations, nor the many other impacts that hydropower development can have on humans and the environment. Project size (in megawatts) is the only performance measure used to quantify power generating capacity gained. This may not be the most important measure, as the size of the project does not necessarily determine the amount of energy it will actually generate. These limited performance measures were developed as a way to begin a conversation of tradeoffs in this basin, but should be considered along with other performance measures and considerations that are not included here.

Additional performance measures should be assessed for these projects in order to gain a greater understanding of their potential impacts to the environment, society and the economy. Some of these may include consideration for the impacts that fragmentation and changes to streamflow may have on other flora and fauna in addition to migrating fish, for people and economic activities displaced by reservoir development, impacts to other water users including water use for irrigation, drinking water supply, industrial use and others, changes to floods and droughts and the benefits or repercussions of these changes for populations within the basin, impacts to sediment transport, water quality, and nutrient transport, and consideration for power generation as well as who benefits from the energy sold outside of Colombia. Despite its limitations, this study contributes new information to the decisions making process regarding hydropower development in Colombia and a methodology to assess impacts and benefits of hydropower. This study also introduces modelling techniques for daily reservoir operations on WEAP which can contribute to improve modelling in the future.

References

Abbasi, T., & Abbasi, S. A. (2011). Small hydro and the environmental implications of its extensive utilization. *Renewable and sustainable energy reviews*, *15*(4), 2134-2143.

"Alerta entre pescadores por llenado de embalse Hidrosogamoso" 9 June 2014. El Tiempo. Retrieved from http://www.eltiempo.com/economia/sectores/llenado-de-hidrosogamoso/14095476

Angarita, H., Delgado, J., Wickel, B., Escobar, M. (2015). Biodiversity, wetland ecosystems and flood risks: Implications of hydropower expansion on the Magdalena River. Factsheet. Published by The Stockholm Environment Institute and The Nature Conservancy.

Antonio, R. R., Agostinho, A. A., Pelicice, F. M., Bailly, D., Okada, E. K., & Dias, J. H. P. (2007). Blockage of migration routes by dam construction: can migratory fish find alternative routes?. *Neotropical Ichthyology*, *5*(2), 177-184.

Blackman, A., Uribe, E., van Hoof, B. and Lyon, T.P. (2012). Voluntary Environmental Agreements in Developing Countries: The Colombia Experience. Resources for the Future. 45pp.

Blanco, J. (2008). Integrated water resource management in Colombia: paralysis by analysis?. *Water Resources Development*, *24*(1), 91-101.

Boehrer, B., & Schultze, M. (2008). Stratification of lakes. *Reviews of Geophysics*, *46*(2).

Caycedo, Carloina (2015) "We Need the River to be Free": Activists Fight the Privatization of Colombia's Longest River. Creative Time Reports. http://creativetimereports.org/2015/03/17/activists-fight-privatization-colombias-magdalena-river/ Accessed 14 Sept 2015.

Corporación Autónoma Regional del Alto Magdalena (CAM) (n.d.) Informe de solicitudes de licencias para generación de energía eléctrica con pequeñas centrales hidroeléctricas." Powerpoint presentation.

Corporación Autónoma Regional del Alto Magdalena (CAM) (2015). *Resolución Licencia y/o permiso No. 2289* (Code. F-CAM-110, Version 2). 2, Oct, 2015.

Cernea, M. (1997). The risks and reconstruction model for resettling displaced populations. World development, 25(10), 1569-1587.

Chapra, S. C. (2008). Surface water-quality modeling. Waveland press.

Chen, S. (2009). Discussion of resettlement cost externalization of water resources and hydropower projects. In Advances in Water Resources and Hydraulic Engineering (pp. 1427-1432). Springer Berlin Heidelberg.

Consititucion Politica de Colombia (1991). Accessed 23 Oct 2015. http://pdba.georgetown.edu/Constitutions/Colombia/colombia91.pdf

CORPOEMA – UPME. (2010) Formulation of a development plan for non-conventional energy sources in Colombia (PDFCNE) 1.

Daware, K. (n.d.). Hydroelectric Power Plant : Layout, Working and Types | electricaleasy.com. Retrieved from http://www.electricaleasy.com/2015/09/hydroelectric-power-plant-layout.html

Decreto 2041 in Decreto Único Reglamentario del Sector Ambiente y Desarrollo (2014). Competencia y Exigibilidad de la Licencia Ambiental Art. 6-28. Retrieved from https://www.minambiente.gov.co/index.php/component/content/article?id=2093:plantilla-areas-planeacion-y-seguimiento-30#decreto-único-hipervinculos

Demarty, M., & Bastien, J. (2011). GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH 4 emission measurements. *Energy Policy*, *39*(7), 4197-4206.

den Ouden, T. (2015). *How hydrologic conditions and energy market dynamics determine hydro power operation and their combined influence on flood hazard and ecology* (Unpublished master's thesis). UNESCO-IHE, Universitat Politécnica de Catalunya, Barcelona, Spain.

dos Santos, M. A., Rosa, L. P., Sikar, B., Sikar, E., & dos Santos, E. O. (2006). Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. *Energy Policy*, *34*(4), 481-488.

Duarte-Abadía, B., Boelens, R., & Roa-Avendaño, T. (2015). Hydropower, encroachment and the re-patterning of hydrosocial territory: The case of Hidrosogamoso in Colombia. *Human Organization*, *74*(3), 243-254.

"El Quimbo se reactiva, pero el debate ambiental no para". 10 January 2016. *El Tiempo.* Retrieved from http://www.eltiempo.com/estilo-de-vida/ciencia/represa-el-quimbo-apertura/16476978

"Este fenómeno del Niño es el segundo más fuerte de nuestra historia". 6 Enero 2016. *El Tiempo* Retrieved from http://www.eltiempo.com/politica/gobierno/sequia-en-colombia-lo-peor-esta-por-venir-dice-santos/16474340

Food and Agriculture Organization of the United Nations (FAO). (2016). *AQUASTAT* Website accessed on 1 January 2016.

Fearnside, P. M. (2004). Greenhouse gas emissions from hydroelectric dams: controversies provide a springboard for rethinking a supposedly 'clean'energy source. An editorial comment. *Climatic Change*, *66*(1), 1-8.

Forero-Medina, G., & Joppa, L. (2010). Representation of global and national conservation priorities by Colombia's Protected Area Network. *PLoS One*,*5*(10), e13210.

Gao, Y., Vogel, R. M., Kroll, C. N., Poff, N. L., & Olden, J. D. (2009). Development of representative indicators of hydrologic alteration. *Journal of Hydrology*, *374*(1), 136-147.

Grill, G., Lehner, B., Lumsdon, A. E., MacDonald, G. K., Zarfl, C., & Liermann, C. R. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters*, *10*(1), 015001.

International Energy Agency (IEA). (1998). Benign energy? The environmental implications of renewable. Paris: International Energy Agency. http://www.iea.org [last accessed March 2010].
International Energy Agency (IEA). (2014). *World energy outlook 2014*. Retrieved from http://www. worldenergyoutlook.org/publications/weo-2014/
IDEAM Agua. (n.d.) Acessed on 23 Oct 2015 http://www.ideam.gov.co/web/agua/
IUCN Red List of Threatened Species. (2013). Version 2013.2 Retrieved from: www.iucnredlist.orgiucn
Jarvis, A., H.I. Reuter, A. Nelson, E. Guevara, 2008, Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database http://srtm.csi.cgiar.org
Jiménez-Segura, L. F., Palacio, J., & Leite, R. (2010). River flooding and reproduction of migratory fish species in the Magdalena River basin, Colombia. *Ecology of freshwater fish*, *19*(2), 178-186.
Jiménez-Segura, L. F., Restrepo-Santamaría, D., López-Casas, S., Delgado, J., Valderrama, M., Álvarez, J., & Gómez, D. (2014). Ictiofauna y desarrollo del sector hidroeléctrico en la cuenca del río Magdalena-Cauca, Colombia. *Biota Colombiana*, *15*(2).
Kavurmacı, M., Ekercin, S., Altaş, L., & Kurmaç, Y. (2013). Use of EO-1 Advanced Land Imager (ALI) multispectral image data and real-time field sampling for water quality mapping in the Hirfanlı Dam Lake, Turkey. *Environmental Science and Pollution Research*, *20*(8), 5416-5424.
Lavaux, S. (2006). Natural resources and conflict in Colombia: Complex dynamics, narrow relationships. *International Journal*, *62*(1), 19-30.
Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94.
Ledec, G., & Quintero, J. D. (2003). Good Dams and Bad Dams. Environmental Criteria for Site Selection of Hydroelectric Projects. The World Bank. Latin America and Caribbean Region Sustainable Development Working Paper, 16, 21. Retrieved from http://siteresources.worldbank.org/LACEXT/Resources/258553-1123250606139/Good_and_Bad_Dams_WP16.pdf
Li, Y., & Chen, F. (2008). Non-uniform sediment transport downstream from reservoir. Transactions of Tianjin University, 14, 263-270.
López-Casas, S., Jiménez-Segura, L. F., Agostinho, A. A., & Pérez, C. M. (2016). Potamodromous migrations in the Magdalena River basin: bimodal reproductive patterns in neotropical rivers. Journal of fish biology.
Lund, J. R. (2000). Derived power production and energy drawdown rules for reservoirs. Journal of Water Resources Planning and Management, 126(2), 108-111.
Lund, J. R., & Guzman, J. (1999). Derived operating rules for reservoirs in series or in parallel. *Journal of Water Resources Planning and Management, 125*(3), 143-153.

MacDonnell, L. J., & Grigg, N. S. (2007). Establishing a water law framework: The Colombia example. Water international, 32(4), 662-675.

Micro-hydro power. (2008, January 10). Retrieved June 1, 2016, from https://www.ashden.org/micro-hydro

Milliman, J. D., & Farnsworth, K. L. (2013). *River discharge to the coastal ocean: a global synthesis*. Cambridge University Press.

Ministerio de Ambiente y Desarrollo Sostenible de la República de Colombia (2016). Accessed 15, July 2016. https://www.minambiente.gov.co/#

Mojica, J. I.; J. S. Usma; R. Álvarez-León y C. A. Lasso (Eds). 2012. Libro rojo de peces dulceacuícolas de Colombia 2012. Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, Instituto de Ciencias Naturales de la Universidad Nacional de Colombia, WWF Colombia y Universidad de Manizales. Bogotá, D. C., Colombia, 319 pp.

Morales, S., Álvarez, C., Acevedo, C., Diaz, C., Rodriguez, M., & Pacheco, L. (2015). An overview of small hydropower plants in Colombia: Status, potential, barriers and perspectives. *Renewable and Sustainable Energy Reviews*, *50*, 1650-1657.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, *50*(3), 885-900.

Northern South America: Western Colombia Ecoregions, WWF. (n.d.). Retrieved August 13, 2016, from http://www.worldwildlife.org/ecoregions/nt0221

Olden, J. D., & Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, *19*(2), 101-121.

Opperman, J. O., Grill, G., Hartmann, J. (2015). The Power of Rivers, Finding balance between energy and conservation in hydropower development. Published by The Nature Conservancy.

Ospina Noreña, J. E., Gay García, C., Conde, A. C., Magaña, V., & Sánchez Torres Esqueda, G. (2009). Vulnerability of water resources in the face of potential climate change: generation of hydroelectric power in Colombia. *Atmósfera*, *22*(3), 229-252.

Pareja-Carmona, M. I., Jiménez-Segura, L. F., Villa-Navarro, F. A., Reinoso-Flórez, G., Gualtero-Leal, D. M., & Ángel-Rojas, V. J. (2014). Áreas de reproducción de peces migratorios en la cuenca alta del río Magdalena, Colombia. *Biota Colombiana*, *15*(2), 40-53.

Parque Nacional Natural Nevado del Huila (2015). Parques Nacionales Naturales de Colombia. Accessed 23 Nov, 2015. https://www.parquesnacionales.gov.co/PNN/portel/libreria/php/decide.php?patron=01.0118

Peña, R., & Medina, A. (2010). *Capacity Estimation Methods Applied to Mini Hydro Plants*. INTECH Open Access Publisher.

Plan de Ordenamiento Pesquero y Acuícola (POPA) de Betania. (n.d.) Retrieved from http://www.huila.gov.co/documentos/P/POPABetaniaTexto.pdf

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E., & Stromberg, J. C. (1997). The natural flow regime: a paradigm for river conservation and restoration. *BioScience*,*47*(11), 769-784.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., ... & Henriksen, J. (2010). The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. *Freshwater Biology*, *55*(1), 147-170.

Pringle, C. (2003). What is hydrologic connectivity and why is it ecologically important?. *Hydrological Processes*, *17*(13), 2685-2689.

Restrepo, J. D., & Kjerfve, B. (2000). Magdalena river: interannual variability (1975–1995) and revised water discharge and sediment load estimates.*Journal of hydrology*, *235*(1), 137-149.

Restrepo, J. D., Zapata, P., Díaz, J. M., Garzón-Ferreira, J., & García, C. B. (2006). Fluvial fluxes into the Caribbean Sea and their impact on coastal ecosystems: The Magdalena River, Colombia. *Global and Planetary Change*, *50*(1), 33-49.

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation biology*, *10*(4), 1163-1174.

Rojas, J., Amaya, A. O., Sanchez, M., & Zambrano, H. I. (2001). Evaluación Ambiental del ecosistema acuático del alto magdalena en el departamento del Huila. *Revista Ingeniería y Región*, *1*, 15-22.

Sachdev, H. S., Akella, A. K., & Kumar, N. (2015). Analysis and evaluation of small hydropower plants: A bibliographical survey. Renewable and Sustainable Energy Reviews, 51, 1013-1022.

Sandoval, J. "Estrategia Colombiana de Desarrollo Bajo en Carbono" Retrieved from https://unfccc.int/files/bodies/awg/application/pdf/3_colombia-revised.pdf

Shen, J., Cheng, C., Zhang, J., & Lu, J. (2015). Peak Operation of Cascaded Hydropower Plants Serving Multiple Provinces. Energies, 8(10), 11295-11314.

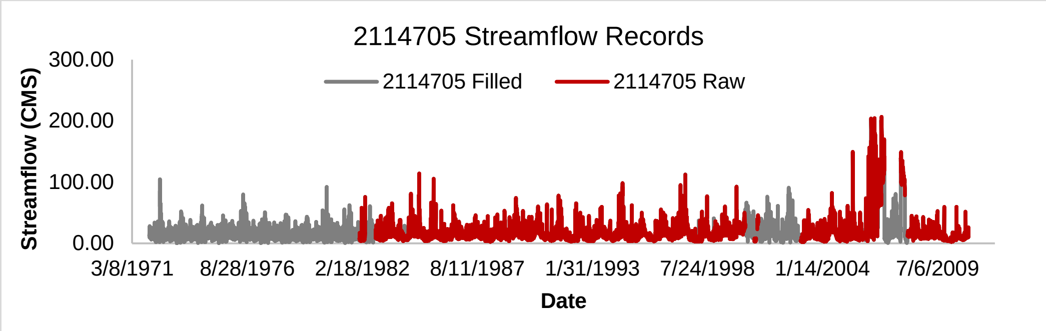
Sneddon, C., & Fox, C. (2008). Struggles over dams as struggles for justice: The World Commission on Dams (WCD) and anti-dam campaigns in Thailand and Mozambique. *Society and Natural Resources*, *21*(7), 625-640.

Stockholm Environment Institute (SEI). (2015). *Ríos del Páramo al Valle, por Urbes y Campiñas, Building climate adaptation capacity in water resources planning* (Final Report). Submitted to The United States Agency for International Development (USAID). Retrieved from https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-USAID-2015-Colombia-final-report.pdf

The Nature Conservancy (TNC) (2015a). Conservation Gateway, ELOHA case study Colombia. Accessed on 15 July 2016. https://www.conservationgateway.org/ConservationPractices/Freshwater/

EnvironmentalFlows/MethodsandTools/ELOHA/Pages/ELOHA-case-study-Colombia.aspx
The Nature Conservancy (TNC) (2015b) Magdalena River Basin Past, Present and Future of Colombia. Accessed 21, Nov 2015. http://www.nature.org/ourinitiatives/regions/southamerica/colombia/magdalena-river.xml
"The Republic of Colombia The Magdalena River Master Plan". Prepared by Powerchina, Hydrochina Corporation, Cormagdalena: December 2013.
UPME (2013). Record Generation Projects November 2013. (Inscripción según requisitos de las Resoluciones UPME No. 0520 y No. 0638).
UPME (2015) Informe de avance proyectos de generación. Technical report, Unidad de Planeación Minero Energético, Medellín, Colombia.
Vogel, R. M., & Fennessey, N. M. (1994). Flow-duration curves. I: New interpretation and confidence intervals. *Journal of Water Resources Planning and Management*, *120*(4), 485-504.
Vogel, R. M., Sieber, J., Archfield, S. A., Smith, M. P., Apse, C. D., & Huber-Lee, A. (2007). Relations among storage, yield, and instream flow. *Water Resources Research*, *43*(5).
XM Compañía de Expertos en Mercados S.A. E.S.P. (n.d.) Informacion inteligente, Oferta. Accessed on 25 Jan 2016. Retrieved from http://informacioninteligente10.xm.com.co/oferta/Paginas/HistoricoOferta.aspx
Yates, D., Sieber, J., Purkey, D., & Huber-Lee, A. (2005). WEAP21—A demand-, priority-, and preference-driven water planning model: part 1: model characteristics. *Water International*, *30*(4), 487-500.
Zhang, J., Xu, L., & Li, X. (2015). Review on the externalities of hydropower: a comparison between large and small hydropower projects in Tibet based on the CO 2 equivalent. *Renewable and Sustainable Energy Reviews*, *50*, 176-185.
Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. A. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences*, *109*(15), 5609-5614.

Appendix



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2114705 Filled
2114705 Raw
Streamflow (CMS)
300.00
200.00
100.00
0.00
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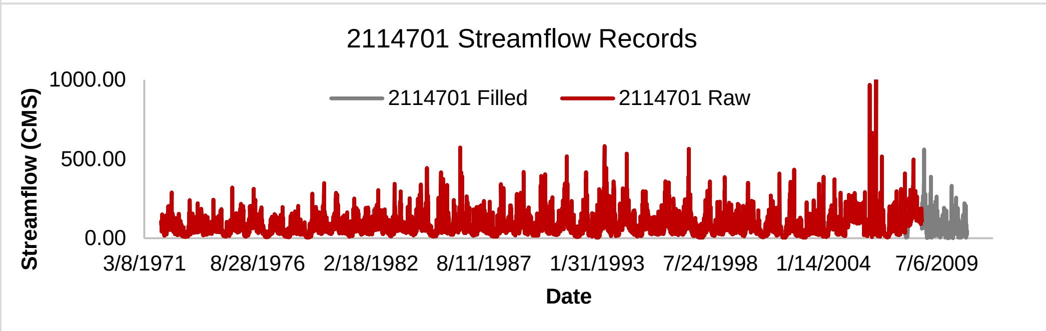
8/28/1976
2/18/1982
8/11/1987
1/31/1993
7/24/1998
1/14/2004
7/6/2009
Date



2114701 Streamflow Records
2114701 Filled
2114701 Raw
Streamflow (CMS)
1000.00
500.00
0.00
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1/31/1993
7/24/1998
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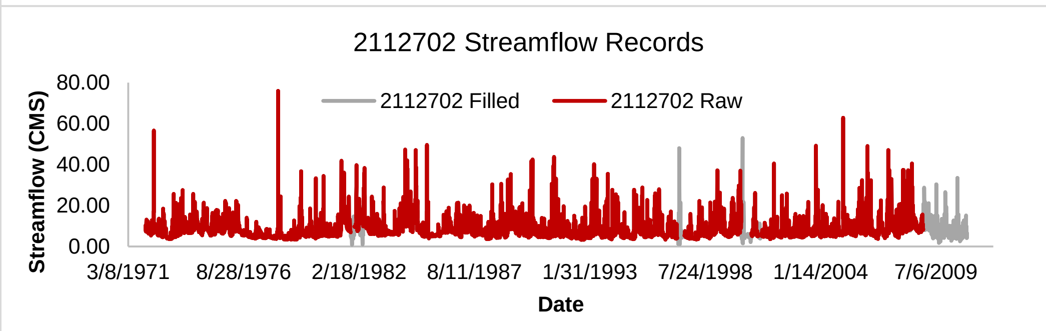
7/6/2009
Date



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2112702 Filled
2112702 Raw
Streamflow (CMS)
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0.00
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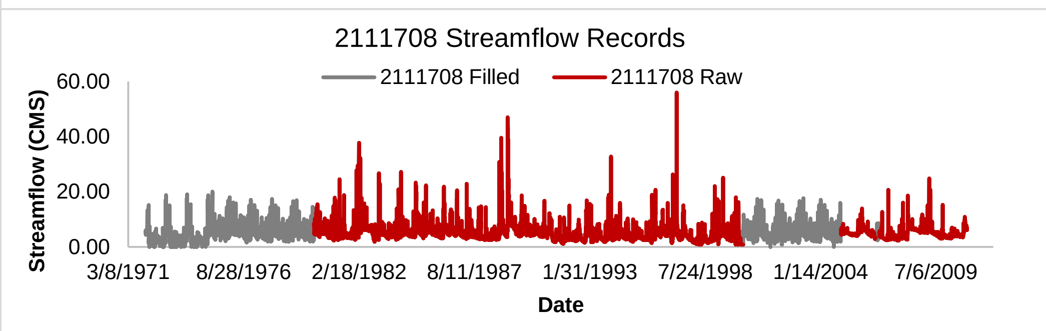
7/24/1998
1/14/2004
7/6/2009
Date



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Date

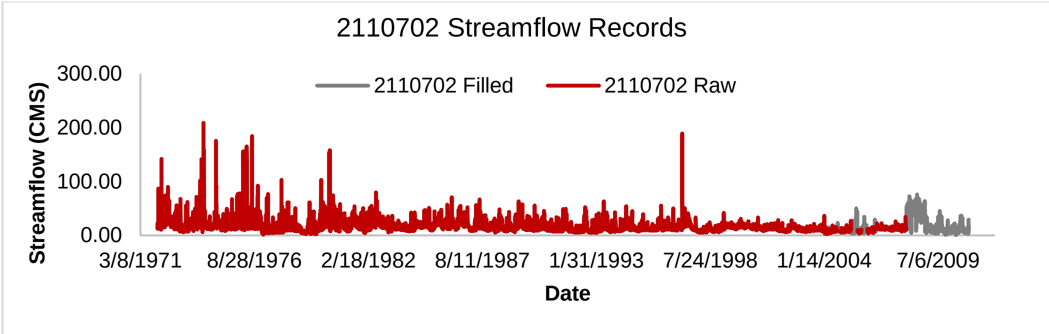

Figure A-1. *Flow records from tributary gauges before and after gaps were filled.*

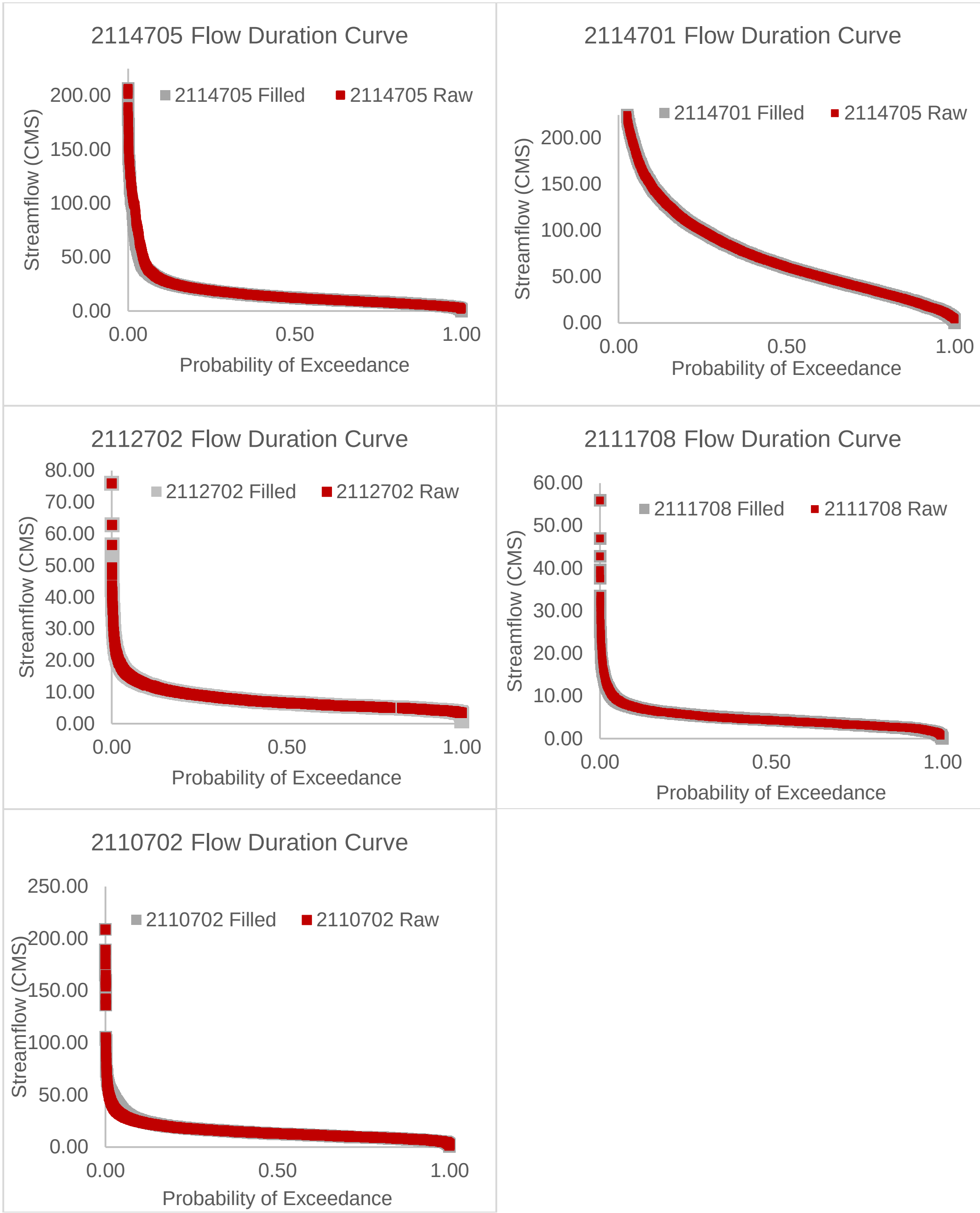

Figure A-2. *Flow Duration Curves for tributary gauges before and after gaps were filled in.*