Biodiversity, wetland ecosystems and flood risks: Implications of hydropower expansion on the Magdalena River

Introduction

The Mompos Depression in Colombia includes one of the largest wetland systems in the world. Annual large-scale inundation of its floodplains and associated wetlands regulates water, nutrient and sediment cycles – which, in turn, sustain a wealth of ecological processes and ecosystem services that are critical to communities' food supplies, in particular fisheries. However, flooding also poses a serious threat to communities, which are often ill prepared for extreme events.

The Magdalena River Basin has great hydropower potential, and there is a growing interest in making the most of it. A number of large hydropower dams are in advanced stages of planning in the upstream reaches of the two largest rivers (out of four) that converge in the Mompos Depression, the Cauca and Upper Magdalena. While these dams are expected to more than double national hydropower production, the implications for the wetlands and the people that depend on them are highly uncertain.

Aiming to ensure that hydropower development is sustainable and does not disrupt key ecosystems and the services they provide, The Nature Conservancy (TNC) has promoted a basin-wide integrated management and planning approach, "Hydropower by Design". As part of this approach, a model of the basin is being developed with SEI's Water Evaluation And Planning (WEAP) system, in collaboration with SEI.

This fact sheet presents the first results of modelling with new WEAP enhancements developed collaboratively by TNC and SEI to capture large-scale floodplain and wetland flooding processes and provide a new way to assess how changes in upstream water resource development practices, including existing reservoir operations and future dam development, could alter these dynamics. Other capabilities to WEAP were also added, including integration with TNC's Indicators of Hydrologic Alteration, a tool to measure the impacts on ecosystems of changes in streamflow due to human activities.

System description

The Magdalena River is the most important waterway in Colombia and South America's fifth largest river. Its main course is more than 1,500 kilometers long, starting among the glaciers and cloud forests of the Andes Mountains in southern Colombia and flowing north to its outlet in the Caribbean at Barranquilla, Colombia's fourth-largest city. It also transports some of the highest volumes of sediment among rivers in South America, with a mean estimated sediment yield of about 690 tons/km^2/year for the Magdalena and its sub-basins.

Fishermen in Pijino, in the lowlands of the Magdalena River Basin.

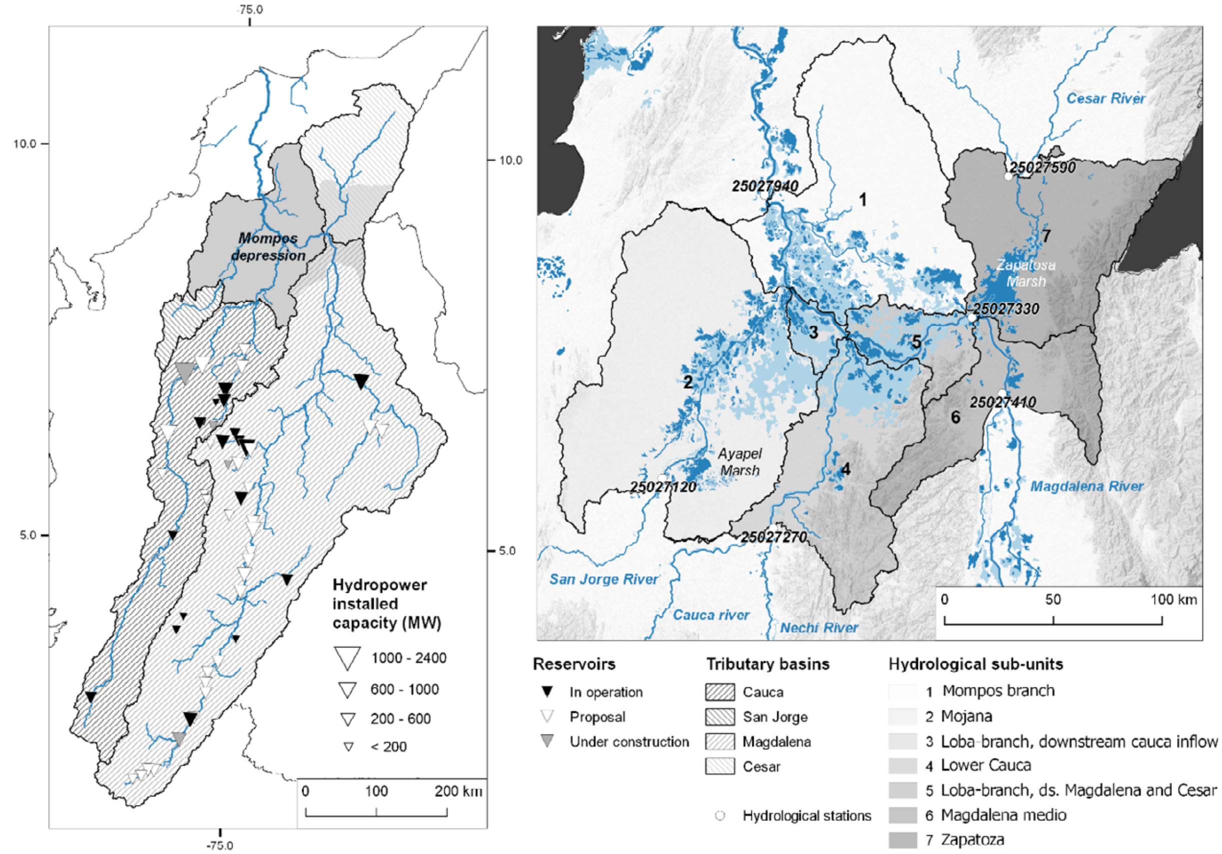

Figura 1: Map of the Magdalena River Basin showing the upstream hydropower reservoirs (existing and projected), location of the low floodplains system, gauge stations referenced in the text.

A large portion of this sediment is deposited in the Mompos Depression, a tectonic basin of roughly 32,198 km², or 11.8% of the total area of the entire Magdalena basin. The flows are particularly heavy during two periods each year, in June and in November–December, due to the oscillation of the Inter Tropical Convergence Zone (ITCZ) over this region. Flooding of the river-associated wetlands of the Mompos Depression is typically an annual event, occurring between October and December.

The heavy flows of sediment, brought by four major rivers – the Magdalena, Cauca, Cesar and San Jorge (see Figure 1) – have created complex morphological and hydrological dynamics that result in high levels of ecological complexity and species diversity in these low-lying wetlands. There are more than 200 indigenous fish species (roughly half of which are endemic), as well as high diversity of mammals, birds and amphibians. The wetlands and lagoons are critical stopovers for birds along the Western Hemisphere migratory flyways. Rural communities depend on these habitats for fish harvest and other resources. The ecosystems, in turn, heavily depend on the seasonal delivery of water, nutrients and sediment brought by flood waters.

Hydropower development in the Magdalena Basin

The Magdalena basin provides 70% of Colombia's hydropower, and the majority of the nation's planned hydropower expansion lies within this basin (see Figure 1). There are already 26 medium and large reservoirs in the basin, with an aggregate installed capacity of 6.36 GW and an annual average production of about 33,400 GWh. Two major dams with a planned total installed capacity of 2.80 GW are under construction. In addition, an inventory of planned hydropower projects over the next decade includes 30 large projects, potentially adding another 7.64 GW of installed capacity.

Dams inevitably alter the flow regime and connectivity of rivers, both longitudinally (upstream and downstream) and laterally (between the river and wetlands), jeopardizing their productivity. This is an important consideration in this region, because of high existing vulnerability to extreme floods. In 2010–2013, a series of floods caused by an exceptionally wet "La Niña" period, resulted in numerous deaths and widespread property damage in the lower Magdalena basin.

Since those floods, several studies have been conducted to identify structural and non-structural measures to manage and mitigate flood risk in this area. However, those studies have not fully considered the implications of climate change and of changes in upstream water management on the flooding dynamics of the wetland systems within the Magdalena basin. The development of hydropower dams is often presented as helpful in controlling floods. Our modelling, however, suggests that at least in this case, it is not.

WEAP floodplain model

A conceptual model including a wetland and floodplain storage component that includes lateral interactions between a river and adjacent flooded areas was developed using an enhanced version of WEAP. (Evaluation of longitudinal connectivity loss is also an active area of model development, but was beyond the scope of the current project.) WEAP was enhanced in two key ways for this project: to include surface water storage in the soil moisture model, and to better represent connections between surface storage and the river network (Figure 2), capturing the complex in-

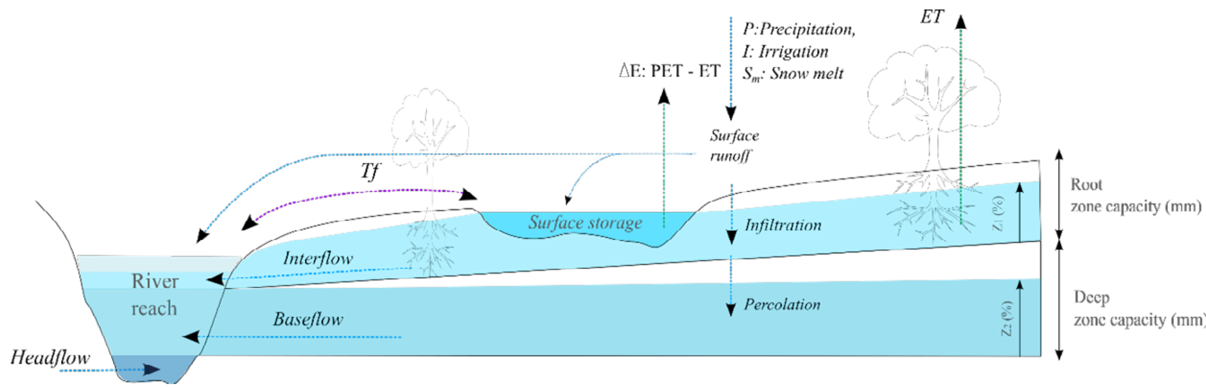

Figura 2: Schematic of the two-layer soil moisture model including a surface storage component, showing the different hydrologic inputs and outputs.

teractions between wetlands, river reaches and floodplains. For example, it is now possible to represent a case where a floodplain is fed by the overflow from multiple river reaches, and/or where the return flow from the floodplain occurs to multiple reaches of the river or transferred to neighboring river objects. The mathematical details of the water balance equations will soon be published in a peer-reviewed journal article.

The WEAP floodplain enhancements allow for an integrated evaluation of water resource management practices, including reservoir operations, planned hydropower development, and in a later stage, the evaluation of climate change impacts. The development of the model focused on the Mompos Depression and adjacent lowlands. The region includes hydrological monitoring stations which, despite shortcomings in terms of record completeness, allowed us to infer patterns of circulation of water within the basin, and a basic validation of the simulated water balances.

The floodplain model was tested under different sets of conditions, based on different definitions of natural hydrological units within the Mompos system, in order to evaluate the importance of floodplain and wetland boundary conditions. The model was calibrated and validated by comparing simulated runoff from each hydrologic unit with observed runoff over a 20-year period (1985–2005). The resulting statistics fell within acceptable ranges for the calibration and validation periods.

Modeling hydropower and floodplain connectivity

The current baseline case in the model includes the 26 existing dams and two under construction. The Degree of Regulation (DOR), which can be used as an indication of how much upstream reservoir operations affect downstream flow, was calculated for each dam, and combined into a cumulative impact. Based on the storage capacity of hydropower reservoirs in 2010, the existing DOR is estimated to amount to 5% of the average annual runoff volume upstream of the Mompos Depression near the Zapatosa Marsh on the Magdalena River.

Current levels of DOR of the flow into the Mompos Depression, are thought to be close to natural conditions (see Figure 3), due to the fact that the existing dams are concentrated in the Magdalena's headwaters (see Figure 1), and a substantial amount of flow originates from the middle and lower sections of its tributaries. Development of all 30 planned projects, bringing the total number of dams to 58, would increase the DOR to about 30% for the Magdalena (see Figure 3).

Based on simulations with the enhanced version of WEAP, we can see that with increasing levels of hydropower development, the hydrograph will become more regular upstream of the Mompos Depression main tributaries. Based on the model simulations, increased regulation is bound to affect the flow regime in very distinct ways.

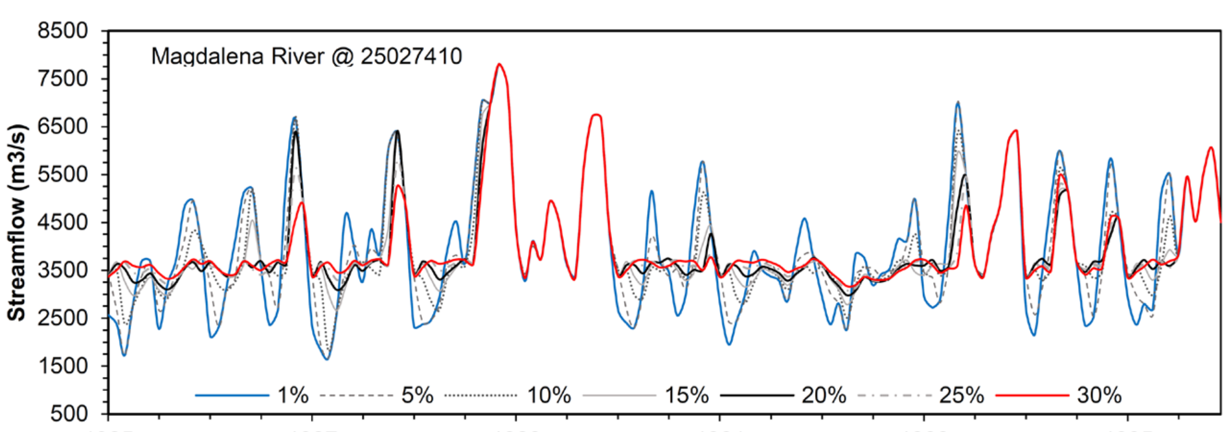

Figure 3: Simulated impacts of upstream regulation between 1 and 30% (expressed as total reservoir volume / average yearly runoff) in wetland dynamics. Simulated monthly hydrographs in the Magdalena River upstream of Zapatosa Marsh and the Mompos Depression resulting from hydropower operations. Regulation capacity equivalent to DOR of 1, 5, 10, 15, 20 and 30%.

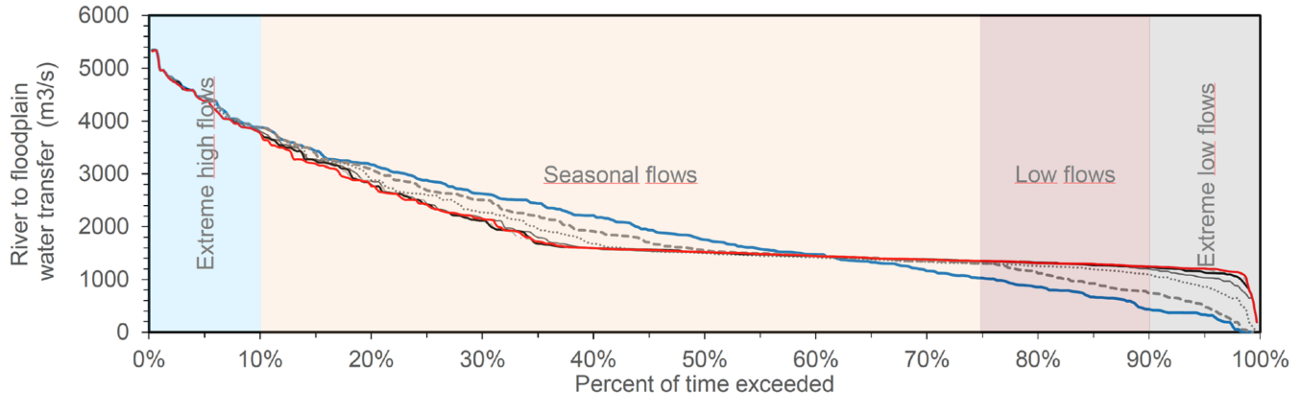

Figure 4: Changes in hydroperiod (time when soil is waterlogged). Extreme high flows, seasonal flows, low flows and low extremes ranges (background colors) of the various flow components are shown. Each of these components has specific relations with the hydraulic and geomorphological dynamics that define the habitats available and therefore define biodiversity and ecological relationships.

High flows: At the highest DOR – equivalent to 30% of the average annual discharge – reservoir operations substantially reduce the magnitude of seasonal flows while virtually eliminating low flow and extremely low flows during dry months (see Figure 4). However, the development of dams is projected to have virtually no impact on extremely high flows/floods, as the extreme high flows (left side of the figure) would continue to occur. The reservoirs would not protect communities from the impacts of extreme floods associated with periodic high flow events (occurring every 10 years or more), such as those that occurred around La Niña in 2010–2011. This is because during peak flow conditions, upstream reservoirs would have to release water for dam safety. One could argue, in fact, that the increased degree of regulation would cause increase risks for downstream communities, as it would likely lead to the development of land that is highly exposed to flooding.

Seasonal flows: Alteration of exchange patterns between the river and wetlands during seasonal flows (center section of Figure 4) could have very severe impacts on local ecosystem functioning, as these are inundation is critical for water, nutrient and sediment delivery to the floodplains and floodplain lakes. These events are critical to reproduction of fish and bird species, for example.

Low flows: Due to higher DOR, base flows are expected to become much higher and much less variable (right section of Figure 4). Even small increases in regulation are expected to result in drastic alterations of low flows, which are important for many aspects of biodiversity and ecological events, such as reptile reproduction, the propagation of riparian vegetation communities, and nutrient and organic matter storage.

The attenuation of seasonal flow exchange between the river and adjacent floodplains and wetlands is illustrated in Figure 5.

Lastly, the new model also allows for the evaluation the implications of potential lateral connectivity loss due to flood control structures such as longitudinal levees and roads. Figure 6 illustrates the peak flow downstream of the Mompos Depression resulting from a loss of connectivity with respect to current conditions. These results indicate that a reduction of system

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The wetlands in the Mompos Depression are home to a rich variety of species, including wading birds such as these wintering Great Egrets.

A view of the coastal city of Barranquilla, where the Magdalena River reaches the sea.

connectivity could produce an increase of up to about 900 m^3/s (+7.2%) in the magnitude of peak flows during extremely wet conditions, such as La Niña 2010–2011, (which historically occur on average once in 30 years on average). This is equivalent to 9.4 billion m^3 of additional floodwaters in the areas downstream of the Mompos Depression, such as the industrial and urban zones of Barranquilla.

Conclusions and next steps

This project addresses the need to find pathways for hydropower development that expand the energy supply, but also work for communities and nature. The WEAP model of the Magdalena River Basin and the Mompos Depression is a useful tool to help identify system-scale solutions. The WEAP enhancements developed through this work allow for a new suite of model studies that can simulate large-scale dynamics of floodplain inundation. This work shows that the dynamics of water storage in the floodplains on a monthly to decadal scale are driven by climatic variations at the basin scale, and can be represented within the model. This makes WEAP the first platform able to successfully resolve the floodplain water balance at medium-to-large scales (about 10,000 km^2), and link the simulation of these dynamics to simulations of water management practices. This tools will be useful to researchers and planners tackling similar challenges around the world.

In terms of management implications, our model estimates that proposed upstream hydropower infrastructure has an aggregate storage and allocation capacity similar to the magnitude of the episodic storage of water on floodplains in the Mompos Depression during average to dry periods (about 15 billion m^3). Cumulative impacts of the operation of hydropower plants would result in alterations of key components of flow regime and wetland dynamics. This emphasizes the need to establish basin-scale water allocation rules that allow for the preservation of floodplain ecosystems dynamics.

Climate change is making both the frequency and intensity of La Niña events increasingly uncertain, and affecting water flows more broadly. In this context, the potential adverse effects of development of water management infrastructure, including the risk of increased vulnerability of communities to extreme floods,

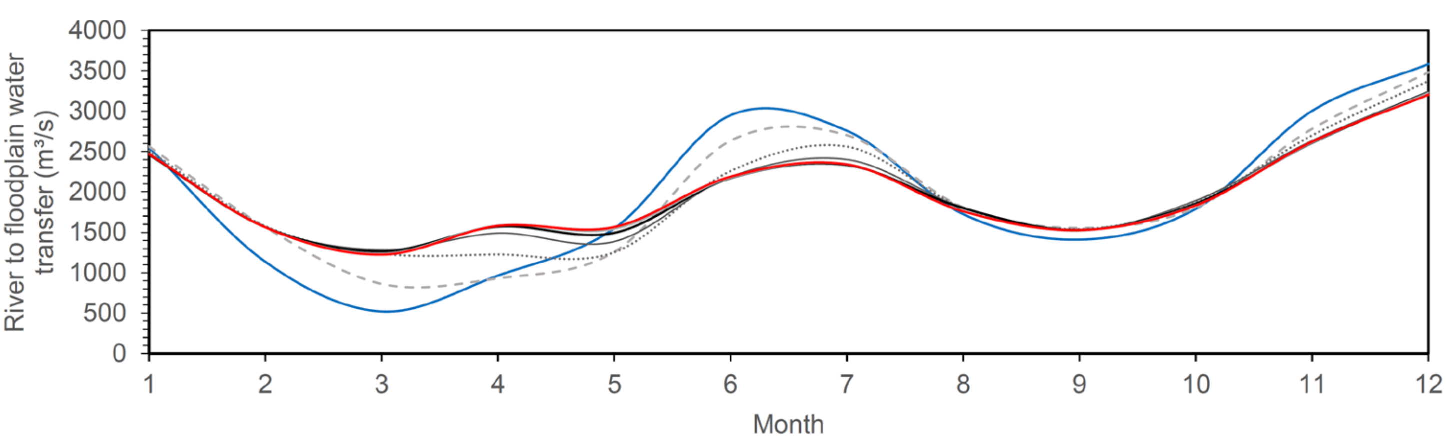

Figure 5: Changes in average seasonal pattern of river and flood plain water exchanges

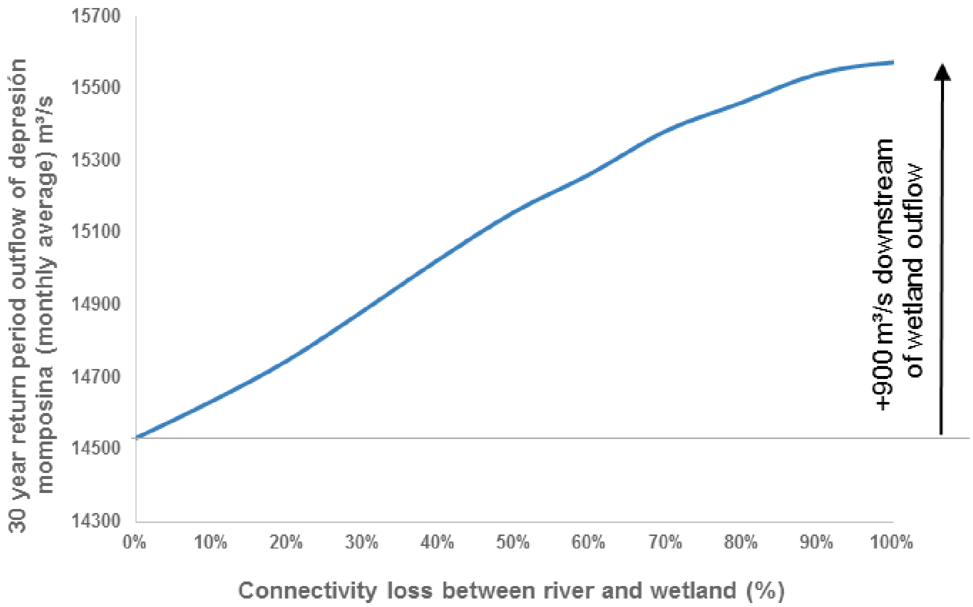

Figure 6: Trade-off of connectivity loss between river and wetlands in terms of the magnitude of extreme peak flow downstream of the Mompos Depression.

need to be carefully evaluated. The potential for creating maladaptive conditions, such as increasing flood risk by reducing medium flow events in this region, is very real.

Sustainable development in Colombia and other countries will require a better understanding of linkages between climate change and variability, water systems operation, and floodplain dynamics. The approach presented here, which can be replicated elsewhere using the enhanced WEAP, can thus provide critical insights to guide infrastructure development and ecosystem conservation projects.

The Ayapel wetland in the Mompos Depression is home to a great variety of flora and fauna, and supports many subsistence fishermen.

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