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Challenges and opportunities for a South America Waterway System

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ABSTRACT

South America has been developed from its coast to its hinterlands since the beginning of its Western colonization. However, to this point, no significant effort has been made to integrate its interior. Waterways transportation can be considered the most sustainable inland mode of transportation due to its low CO_2 emissions per ton of cargo transport. With this in mind, this paper investigates the history, challenges and opportunities of the past proposals for the construction of the South America Waterway System (SAWS) connecting the La Plata, Amazon, and Orinoco river basins. It focuses on particular challenges of the proposed waterway. (i) a comparison between the deforestation surrounding existing road and waterway infrastructure in the Amazon, (ii) the large water level variation in the Amazon basin, (iii) and the alternatives for storing water to reduce the impacts of floods and droughts in the proposed waterway. We conclude that deforestation surrounding existing waterways is practically zero and that groundwater storage has an important role in storing water for the basin and reservoirs, a limited one. The SAWS can significantly foster South American integration, encourage sustainable extraction of natural resources in the region and help the conservation of the Amazon forest.

1. Introduction

Up to the 1950s, the South American economy was geared to the export of primary products, largely transported via river and rail. With the acceleration of the industrialization process in the second half of the twentieth century, public planning shifted in favor of the road sector, to the detriment of railroads, especially in heavy industry and mineral extraction. As a result, the road highway network, the most expensive transport mode for cargo freight after the air mode, moved most of the cargo in South America by the turn of the century (Wilmsmeier and Spengler, 2015).

Waterway transport is the cheapest mode of inland cargo transportation (Caris et al., 2014). It is also the most energy-efficient mode of transport (Tolliver et al., 2013) and the inland transport with the lowest CO_2 emissions per cargo transport (Feng et al., 2019). Inland water transportation is also an important driver of regional economic development (Dávid and Madudová, 2019). A recent study (Lu and Yan, 2015) shows that the break-even distance to make an inland waterway viable compared to road transportation is approximately 195 km. It also has lower impacts on its surrounding areas, particularly when compared to roads and railways (Rohács and Simongáti, 2007). Moreover, inland water transport has been successfully implemented in Europe (Merchan et al., 2019), China (Stefaniec et al., 2020), India (Praveen and Rajakumar, 2015), Bangladesh (Awal et al., 2014), Nigeria (Chukwuma, 2014), Canada (Zheng and Kim, 2017), Brazil (Furtado et al., 2020) and has been under expansion in Myanmar (Nam and Win, 2014), among other nations.

South America has one of the world's highest potentials for waterways, given its relatively flat topography and large water availability (Fig. 1). However, waterways' full potential has not yet been explored in

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South America. For example, most of the region's hydroelectric dams have valuable waterway transport potential, but most of them were built without locks (Figueiredo et al., 2015). This trend has continued with the new dams being built in the Amazon basin, especially in the Xingu, Madeira and Tapajos rivers.

A few proposals for the South America Waterway System, interconnecting the Orinoco, Amazon and La Plata basins have been made. The project was first proposed by Alexandre von Humboldt and Carl von Martius in 1808 (Kohlheep, 2005), then by Eduardo Moraes (1894) and President Sarmiento (Argentina) in the 19th century. Later, Deputies Gabriel del Mad (Argentina) in 1948, and Vasco Neto (Brazil) in 1973 presented two projects with the same idea in their respective Houses of Representatives (Gioia, 1987). The former Peruvian president, Fernando Belaunde Terry was one of the principal supporters of the project in 1981. The Pan American Union of Engineers and the South American Union of Engineers also made a strong endeavor to spread the project (Gioia, 1987). Two Venezuelan brothers, Constantino and Paul Georgescu, made an expedition for two years 1979/81) by boat, covering about 40,000 km on the rivers of the three systems and proved the technical feasibility of the project. Interconnecting the three great river basins of South America would be a technical undertaking far less expensive or difficult than building the Panama Canal and the Mississippi-Missouri-Ohio river system in the USA (Georgescu and McGrath, 1990). More than 92% of the 10,000 km of the SWAS can already be navigated eight months a year by boat drafting 1.2 m of water. Only three portages, comprising 680 km, impede interconnecting the three basins. Approximately 10,808,870 km^2 in the interior of South America, more than 60% of the continental area. At present, the project is known to be technically viable, however, it has to overcome complex issues prior to its realization. Further background on the waterway's history is presented in (Paz-Castillo and Kruger, 1972).

Recently, the concept was taken up by the Development Bank of Latin America (Georgescu, 2013) and the South American Regional Infrastructure Integration Initiative (IIRSA) (International Rivers Network, 2005) to encourage the circulation of products, services and people while preserving the environment and regional customs. The Paraguay-Parana waterway has considerably increased South American integration. Uniting the region's several river basins has historically been the quickest shortcut to regional economic integration and prosperity for the people of South America. Each basin considered for the proposed waterway already has its operational waterways (Table 1).

According to (Gioia, 1987), civil engineering work must be done to make the SAWS navigable for flat-bottomed barges and small boats with drafts of up to 1.2 m along the whole length of the waterway. The estimated cost for the waterway was 1.4 billion USD in 1987, which would be equal to 3.6 billion USD in 2022 adjusted for inflation. The main works are: (i), the junction of the Paraguay and Guapore rivers; (ii) the Casiquiare canalization; (iii) the removal of rapids and waterfalls on the Madeira and Mamore rivers between Guajara Mirim and Porto Velho; (iv) the removal of rapids and waterfalls in Sao Gabriel; (v) the removal of rapids and waterfalls on the Orinoco; (vi) cater for the significant water level variation, particularly in the Amazon basin; (vii) create large water storage reservoirs to reduce the impacts of flood and drought events in the operation of the waterway.

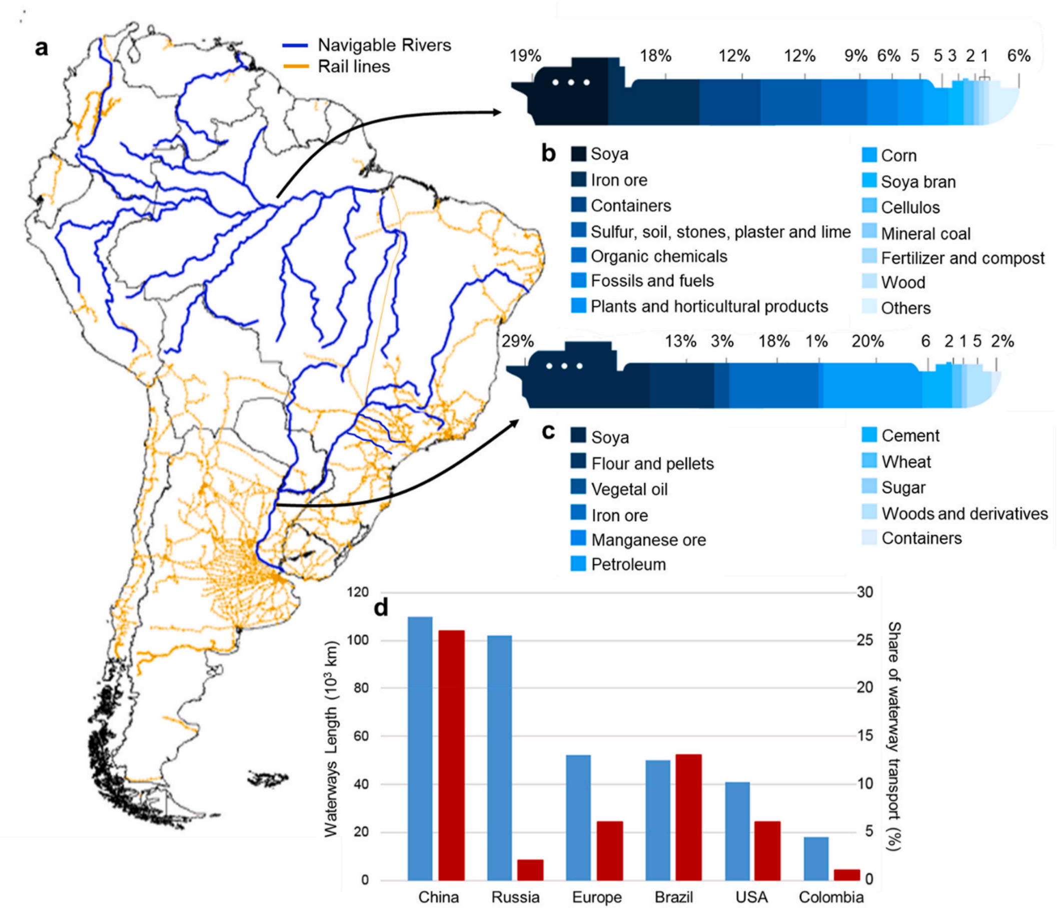

Fig. 1. Navigable rivers in South America. (a) navigable rivers and rail lines in South America. Figure from (Wilmsmeier, 2007). (b) share of transported goods by inland navigation in the Amazon River. Figure from (World wide inland navigation network, 2019a). (c) share of transported goods by inland navigation in the Paraguay-Plata River. Figure from (World wide inland navigation network, 2019b). (d) relevant countries' navigable waterway length and share of inland waterway cargo transportation. Figure from (Wiegmans and Konings, 2017).

Table 1
Characteristics of the existing waterways in the Plata, Amazon and Orinoco basins. Table created by the author.

Basin	Description	Disadvantage	Advantage	Countries
Paraguay, Plata	- 3442 km long (Projects in Bolivia, 2019). - Vessels usually carry soybeans, rice, corn and wood, cement, iron ore and manganese derivatives (Brazilian Department of Transport Infrastructure, 2018).	- Sedimentary and unconsolidated material. - High winding rate. - High sedimentation rate, requiring constant dredging (Brazilian Department of Transport Infrastructure, 2018).	- The average slope is very low 2–6 cm/km. - Slow flow velocity along the entire waterway. - Low requirement for building locks (Brazilian Department of Transport Infrastructure, 2018).	Brazil, Bolivia, Paraguay, Argentina, Uruguay
Negro, Amazon, Madeira, Guaporé	- More than 50,000 km of operational waterways.	- Very high river level variation of up to 18 m hinders navigation and port infrastructure. - Logs and wood debris in the river. - Very high sedimentation rates. Regular bathymetric updates are required (Brazilian Transport Ministry, 2012).	- A vast network of rivers interconnected. - A small number of navigation locks is required. - Low river gradient and river flow speeds. - Transporting soybeans, corn, containers and sugar. (Brazilian Transport Ministry, 2012).	Brazil, Bolivia, Venezuela, Colombia, Peru
Orinocco	- The river mouth on the North coast of Latin America. Or on the Midwest of the Atlantic Ocean.	- High river level variation of up to 18 m. - High sedimentation rates. Regular bathymetric updates are required.	- A small number of navigation locks is required.	Venezuela, Colombia

This research aims to provide an original assessment of the environmental and technical viability of building a South America Waterway System. Particularly focusing on comparing the deforestation surrounding existing road and waterway infrastructure in the Amazon, analyzing the large water level variation in the Amazon basin, and investigating alternatives for storing water to reduce the impacts of floods and droughts in the proposed waterway. It also provides a brief prospective analysis of such a large infrastructure development potential while pointing out future research to further understand the major risks, uncertainties and potentials associated with this waterway system. This paper is divided into five sections. Section 2 presents the methodology of the paper. Section 3 presents the results of the paper. Section 4 discusses the paper. Section 5 concludes the paper.

2. Methodology

Fig. 2 presents the methodological framework applied to explore some relevant technical aspects of the South America Waterway System.

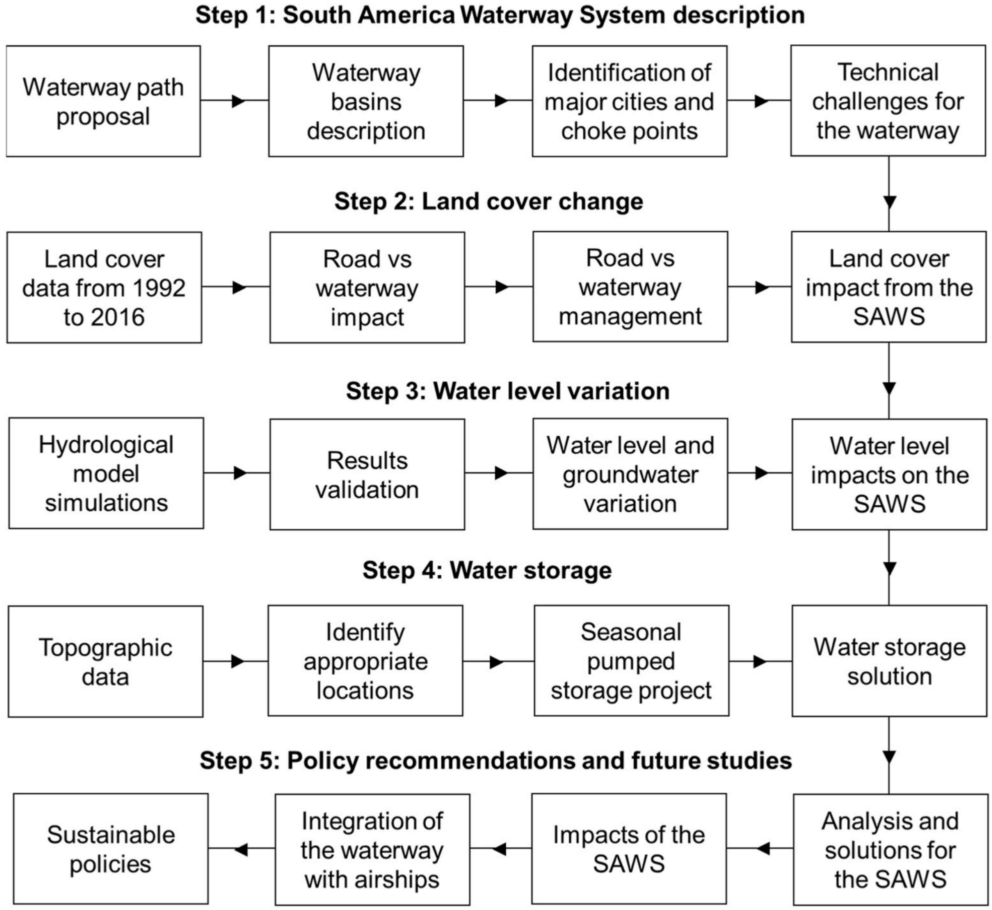

Fig. 2. South America Waterway System technical aspects methodological framework. Figure created by the authors.

It is divided into five steps. Step 1 consists of the description of the South America Waterway System. It outlines the waterway path proposal, identifies the major cities and choke points in the proposed waterway, and briefly describes the major challenges for implementing the waterway.

Step 2 gathers Amazon land cover change data from 1992 to 2016 to compare the deforestation around the existing waterways and road infrastructure. It them proposes strategies to manage the transport of goods along the waterway. Step 3 consists of estimating the water level variation of the Amazon basin throughout the proposed waterway. It runs hydrological model simulations to estimate the water level of the rivers in the Amazon River basin and validate the results from the model. The water level and groundwater variation levels results are found. The impacts on the construction and operation of the waterway are analyzed. Proposals to minimize these impacts are discussed. One of the most relevant solutions to minimize the impact of the large water level variation of the waterway is to store water from the wet to the dry period. Step 4 assesses the potential for storing water in the interconnection between the three basins to allow its operation throughout the year and during drought years. It consists of gathering topographic data, and identifying appropriate locations to build storage reservoirs and analyze the storage capacity of each reservoir. Step 5 consists of proposing policy recommendations and future studies required for the implementation of the South America Waterway System. It estimates the impacts expected from the SWAS, and proposes policies to guarantee the region's sustainable development after the waterway's construction, including integration of the waterway with airships to reduce the reliance on road infrastructure.

The proposed South America Waterway System is presented in Fig. 3. It starts in Argentina in the Plata River. When it reaches the division between Argentina and Paraguay, it changes to the Paraguay River. It continues through Paraguay, Brazil and Bolivia until it reaches the Guapore and Mamore rivers in the Amazon Basin, bordering Brazil and Bolivia. It connects to the Madeira, Amazon and Negro River until it reaches Venezuela. In Venezuela, the waterway changes to the Orinoco River, passing through Colombia and Venezuela until it ends up in the Caribbean Sea. The authors created the waterway path proposal using Google Earth and topographic data. The methodology applied considers the minimum altitude for the interconnection between the different basins and then looks for the shorter distance to connect the three main basins with existing tributary rivers. Fig. 3 also shows the existing run-of-the-river dams, proposed run-of-the-river dams, basin interconnections, proposed seasonal pumped hydropower plants and major cities.

2.1. Land cover change

Land cover data were obtained from the European Space Agency Climate Change Initiative's Land Cover (ESA-CCI) project.[1] The data provide annual maps of land cover maps from 1992 to 2016 at a 300m spatial resolution. ESA dataset is generated by combining the data from four remote sensing instruments, namely, the Medium-spectral Resolution Imaging Spectrometer (MERIS), AVHRR (1992–1999), SPOT-Vegetation (1999–2012), and PROBA-V (2013–2015). The dataset follows a LULC classification defined by the UN Land Cover Classification System (LCCS). It is worth noting that this research was not aimed at assessing the impacts on land and water biodiversity and/or social changes, such as on indigenous communities. The approach focuses on exploring the technical possibility of building an integrated waterway system in South America and suggesting possible auxiliary technologies and management schemes to reduce potential environmental impacts.

2.2. Water level variation

The water level is crucial in inland waterway transportation (Christodoulou et al., 2020). To estimate the river level variation of the waterway, we employed the simulations from a high resolution (1 arc-minute; ~2 km), physically-based continental-scale land hydrology model, LEAF-Hydro-Flood (LHF). LHF is originally derived from Land Ecosystem–Atmosphere Feedback (LEAF) (Walko et al., 2000) and is updated by including schemes for resolving various land surface hydrologic and groundwater processes on a full physical basis (Chaudhari et al., 2019). LHF was setup for the entire Amazon River basin (~7,100, 000 km^2), and regions surrounding the Amazon, such as the Tocantins River basin. Simulations were conducted for the 1980–2015 period with identical settings as in our recently conducted study over the Amazon (Chaudhari et al., 2019). Dynamic monthly LEAF area indices and annual Land Use Land Cover (LULC) maps are incorporated in the model simulations to account for the LULC changes occurring over the years in the Amazon basin. The LHF model results, such as streamflow, water table depth, surface flooding and terrestrial water storage (TWS), have been extensively validated using several ground- and satellite-based observational datasets (e.g., GRACE) over the entire Amazon basin Miguez-Macho and Fan (2012a) and other parts of the world (Shin et al., 2019). More information on the LHF model setup and input data used in the simulations can be found in (Chaudhari et al., 2019).

For better visualization, the original LHF model simulations are upscaled from 1 arcmin spatial resolution to 0.1° degrees. Water level climatology is estimated by temporally averaging the daily water levels simulated by the LHF model over a period of 36 years (1980–2015). Subsurface water storage anomalies are obtained from the LHF model (Chaudhari et al., 2019), which incorporates the soil moisture and groundwater storage expressed as basin averages. Simulated streamflow estimates are also obtained from the LHF model (Chaudhari et al., 2019).

2.3. Water storage

The methodology applied to find appropriate storage reservoirs to reduce the water level fluctuation of the rivers of the waterway is described as follows: (i) analyze the topography of the basins visually (topographic-map.com, 2020) at 500 km from the interconnection of the different basins and 50 km from the waterway. These distances intend to reduce the proposed reservoir's costs and supply water for the interconnection, where water availability is mostly scarce (Slapgard, 2012). (ii) after a few possible reservoir locations have been located, topographic data from the Shuttle Radar Topography Mission (Jarvis A., H.I. Reuter, A. Nelson, 2008) is used to calculate the volume storage capacity of the reservoir. (iii) the design of the plant and cost of the projects are then implemented using the methodology described in (J. Hunt et al., 2020).

3. Results

To provide a comparative case study, we compare the proposed waterway integration in South America with an existing inland water transport project in North America, the USA-Canada Waterway (UCW) (Fig. 4ab). The UCW and the SAWS are roughly 5750 km and 9200 km long, respectively. The UCW has a maximum height of 180 m, while the SAWS would have to overcome two basin transfers: one between the Orinoco and the Amazon basin, with 120 m, and another between the Amazon and La Plata basin, of 240 m. The UCW has the Great Lakes at the top of the waterway, which allows for a dynamic operation and linkage to several cities surrounding the 244,106 km^2 area of the Great Lakes. It also provides a constant amount of water for the operation of the waterway. The SAWS encircles the Amazon basin, which has more than 50,000 km of navigable waterways. Water management and storage is a considerable issue for the SWAS, which threatens year-around

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[1] See more at: http://maps.elie.ucl.ac.be (last access: 22 August 2020).

Fig. 3. South America Waterway System highlighting the relevant country divisions, water basins and rivers. Figure adapted from (FAO – AQUASTAT, 2011).

operation as discussed in this paper.

The UCW connects eight important cities in North America (Montreal, Toronto, Buffalo, Detroit, Chicago, Saint Louis, Memphis, and New Orleans) with highly productive agricultural fields and industrial hubs. The SAWS connects important cities (Ciudad Bolivar, Manaus, Porto Velho, Cuiabá, Buenos Aires, and Montevideo); and navigates through the Amazon forest, the Pantanal, and other important protected environmental areas. The SAWS would require detailed regional plans to preserve these critical biomes, environmental impact assessments, and new surveillance systems, a transparent public consultation process with local communities and authorities.

The interconnection between the Orinoco and the Amazon basin current consists of a naturally occurring canal Fig. 4 c. The Casiquiare Canal, or the Cachequerique River, is a 326 km long natural canal that runs between the left bank of the Orinoco River in Venezuela and the right bank of the Negro River, a tributary of the Amazon River. The channel is a rare geographical occurrence resulting from the river capture of a fork in another watercourse. In a way, this natural connection forms a huge river island encompassing the region of the Brazilian state of Amazonas northeast of the Solimões and Amazonas rivers, the Brazilian states of Amapá and Roraima, Venezuela to the east of the Orinoco and the three Guianas. A recent study estimates that the Casiquiare River takes a significant proportion of flow (20%–30%) from the Upper Orinoco basin to the Amazon basin (Laraque et al., 2019).

The interconnection between the Amazon and Plata basins is more complex than the Orinoco – Amazon basin connection. Firstly, it will be required the construction of locks in the Madeira River dams (the existing Santo Antônio, Jirau, and proposed Binational Brazil-Bolivia Guayaramerin) (Oliveira, 2011) (Fig. 4 a). The interconnection of the Prata and Amazon basins would involve digging a 12 km channel along the edge of the Pantanal, connecting the Aguapeí and Alegre rivers, both born in the Aguapeí Mountains (Lino et al., 2008). The maintenance of the upper section of the Paraguay-Paraná waterway involves multi-stakeholder involvement across different sectors in Brazil, which represents a major governance challenge. To improve the operation and maintenance of the waterway, well-structured plans need to be developed, implemented and reinforced (Schulz et al., 2017, 2018). For other proposals for the connection between the Amazon and Plata basins see (Killeen, 2007).

As shown in Fig. 4 (d), the SWAS waterway can expand its operation at land levels below 250 m and could connect all colored areas in the continent, which consist of 36% of the South America continental area, at low investment costs and with considerable benefits for regional integration. Waterways may have lower investment costs and environmental risks when compared with roads and railways. This would represent a significant boost in the continent's transport infrastructure and has the potential to reduce transportation costs and increase opportunities for new commerce.

Technical aspects involving the Amazon, Orinoco, and Plata rivers create logistical challenges that discourage the construction of the waterway, including the (i) environmental impact and deforestation, (ii) extended dry season and water storage, and (iii) river level variation. Additional issues in the construction or expansion of South American waterways have been discussed in (Ministério dos Transportes, 2015).

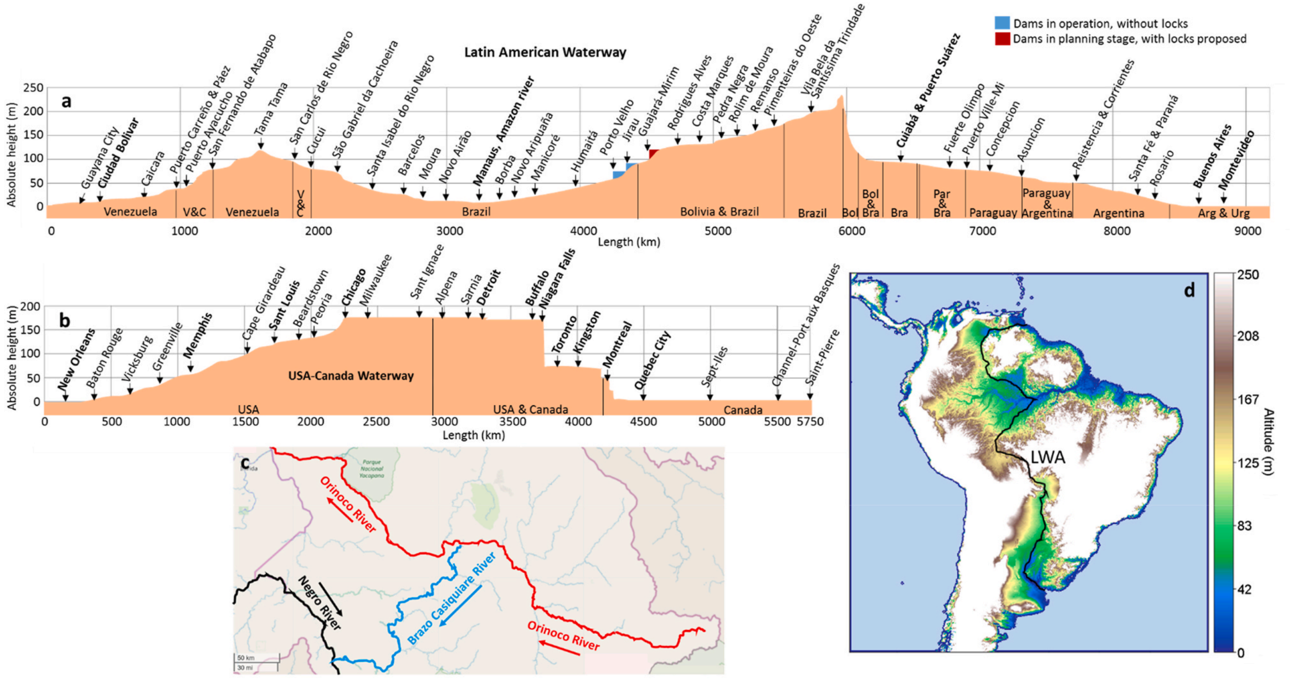


Fig. 4. The South America Waterway System (SAWS). (a) proposed waterway with the indication of the main cities crossed by the waterway and obstacles to be eliminated through the construction of Santo Antônio, Jirau and Bi-national dams (Rezende, 2009). (b) height and length compared with the USA-Canada waterway. (c) the Orinoco and Amazon basins are connected by the Brazo Casquiare River, a natural canal, which considerably facilitates the construction of the South America waterway. (d) topographic map of South America, limited to a height of 250 m, showing the area that can be accessible by the proposed waterway. The authors created all figures.

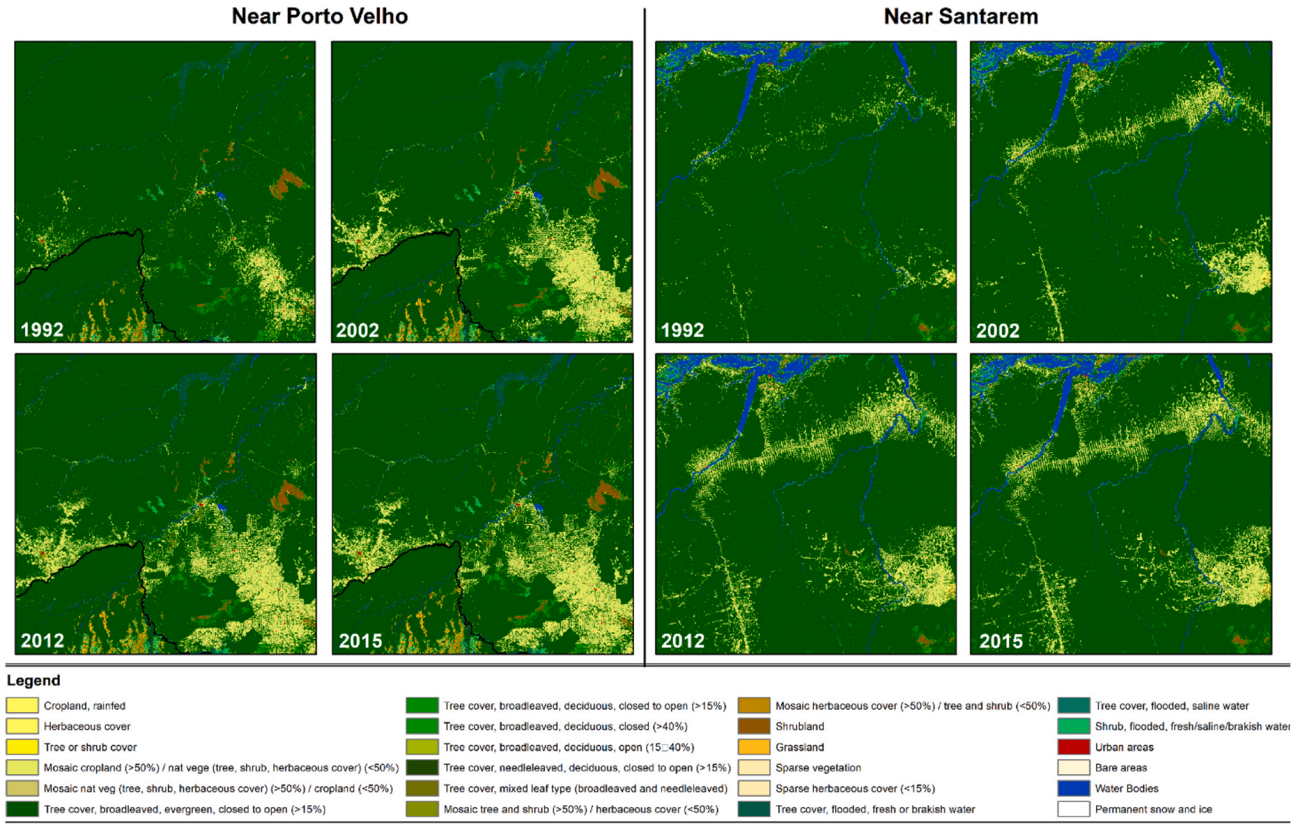


Fig. 5. Amazon forest land change from 1992 to 2015. The map of the Amazon forest shows more deforestation near roads compared to existing waterways. Figure created by the authors.

3.1. Land cover change results

Analyzing the results from land cover change in the Amazon basin presented in Fig. 5, road construction in South America is the main driver of deforestation of the Amazon forest. In contrast, also shown in Fig. 5, deforestation around existing waterways in the Amazon basin is negligible (Lapola et al., 2013). These observations have also been highlighted in (Houghton et al., 2000).

The reasons behind the significant difference between the observed deforestation surrounding roads and waterways in the Amazon region can be divided into three main aspects: (i) access to the forest, (ii) high river water level variation, (iii), monitoring of illegal deforestation. The access to the forest has to be done by roads so that deforestation can happen. Access to the forest via waterways would require a minimum port infrastructure, which would be an easy target for policies to combat illegal deforestation. Also, two transportation modes will be required, increasing the deforestation activity's sophistication and vulnerability. The high river level variation floods road accesses surrounding the waterways during the wet period. The wet period is particularly interesting for deforestation because surveillance from space is ineffective due to the region's thick cloud coverage. The high river level variation would also increase the minimum infrastructure cost to build and operate a port, reducing the viability of used waterways for deforestation. Monitoring illegal deforestation inside the forest is complex, as there are a dozen different roads that can be used to transport the illegal wood. Also, illegal wood and trucks can be easily ridden in the forest in case of surveillance activities. On the other hand, monitoring a waterway is much simpler, as one monitoring station can control the transport of goods of a whole watershed, making illegal logging monitoring significantly easier.

If the SAWS is built, its construction and operation should be closely monitored to avoid deforestation. Local and national laws would be required to protect the forest surrounding the waterway. Careful consideration must be given to how the waterways will be operated and

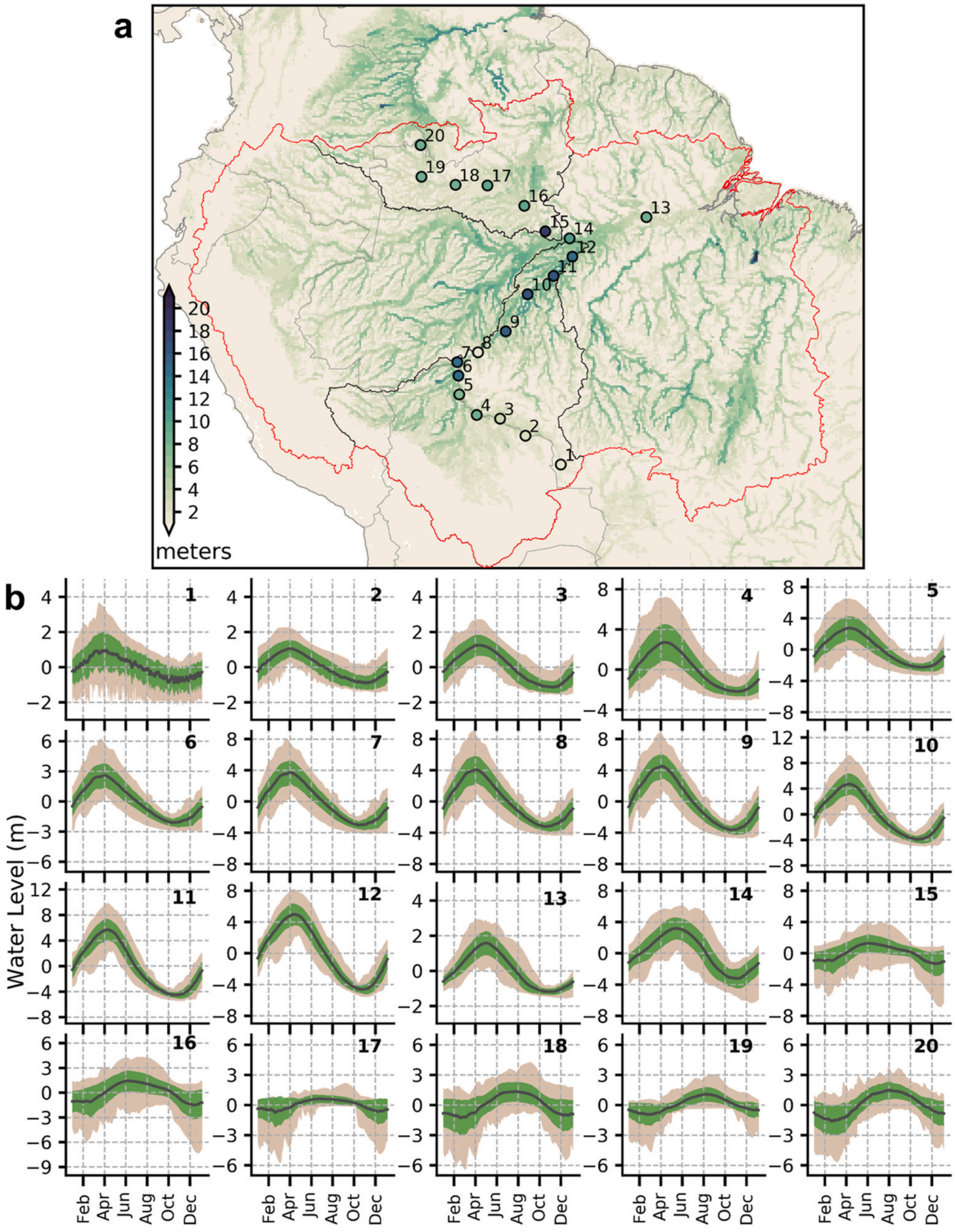


Fig. 6. Water level in the Amazon Basin, (a) maximum river level variation, (b) seasonal water level variation. The authors created all figures.

which types of goods and ships can be transported by the waterway. For example, a consideration of economic activities that would make use of the waterways is essential, such as mineral extraction, agricultural and livestock products, container ships, oil and gas products, hydrogen, biofuels, ammonia, biomass, public transportation, tourism, etc. The infrastructure and land cover change needed to support these industries would likely have adverse consequences on forested lands. In addition, an analysis of pollutants resulting from the transportation of (chemicals, solids, liquids) is needed to better understand their effects on the environment and wildlife.

3.2. Water level variation results

Fig. 6 (a) presents the maximum water level variation simulated by the LHF model (Chaudhari et al., 2019) upscaled to 0.1° grids. Variations are calculated as the difference between the minimum and maximum water levels in the daily climatological mean for 1980–2015. The circles present the observed water levels at 20 locations along the waterway. The river with the highest water level variation is the Madeira River (points 6, 7, 8, 9, 10, 11, 12), with a maximum variation of 18 m and an average variation of 16 m (Fig. 6 (a)). The second highest variation is the Negro River (points 15, 16, 17, 18, 19, 20), with a maximum variation of 20 m and an average variation of 11 m. The third is the Amazon River (points 13, 14), with a maximum variation of 10 m and an average variation of 10 m. The fourth is the Guapore/Mamore rivers (points 1, 2, 3, 4, 5), with a maximum variation of 8 m and an average variation of 4 m. This high water level variation is because the river's elevation above sea level is low, and the distance to the ocean is very large. For instance, the Madeira River near the Bolivian border has a minimum river level of 95 m above sea level and is around 2.400 km from the ocean. This result in an average river slope of 0.00004 (horizontal/vertical distance). To increase the slope and river flow area during the wet season, so that the water may drain into the ocean, the river level must rise by around 18 m.

Fig. 6 (b) shows the climatological mean (1980–2015) seasonal water level anomalies (solid black line) for the 20 selected locations. Shaded areas in green represent one standard deviation from the climatological mean, and those in brown represent the maximum and minimum daily levels during the 36 years. The maximum water level of the different rivers happens at different months. The maximum level in the Guapore river happens in March, Madeira in April, Amazon in June and Negro in August. This is particularly interesting because the waterway locks can be built with the possibility of pumping water from the lower to the upper reservoir. This would allow water from the Negro

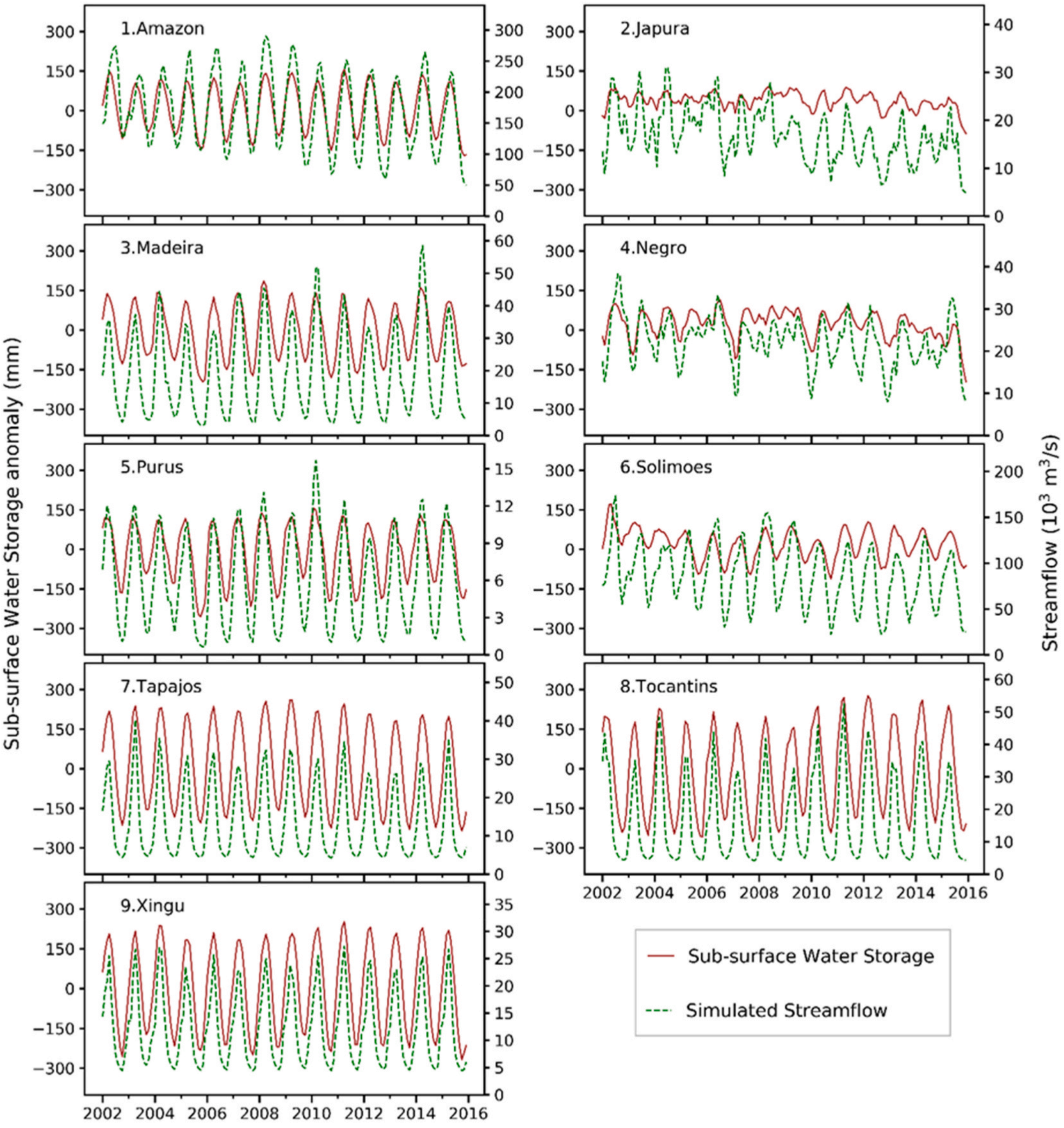


Fig. 7. River flows and groundwater storage in the Amazon basin. The authors created all figures.

river to the pumped to the Madeira, Guapore, Paraguay and Plata Rivers from August to October. Similarly, water from the Madeira River can be pumped to the Negro and Orinoco Rivers.

Fig. 7 presents the results obtained from the LEAF-Hydro-Flood (LHF) model (Chaudhari et al., 2019). Sub-surface water storage anomaly represents the entire basins indicated and comprises of the soil moisture and groundwater storage components as simulated by LHF. Individual basin extents are presented in Fig. 6 (b). This increase in river level results from the significant increase in underground water storage in the basin. The water is stored in the basin because of the limited capacity of the river to discharge water to the ocean. This characteristic can be used to the advantage of the SAWS by maintaining the river level high during the dry period with the dams and locks in the waterway. The control of water discharge by the lock would retain the water stored within the sedimentary soil, thus, saving water to be used during the dry period (Hunt et al., 2022b). A low-head dam would be required to maintain the water level of the river high. If the river levels are maintained high after the end of the wet period, large amounts of water will be stored in the ground (Frappart et al., 2014). This would provide some level of regulation of the flow of the rivers, which would increase the water availability for the waterway and allow it to operate uninterruptedly during the dry period. An evaluation of the impact of the construction and operation of these storage reservoirs on the surrounding land and the climate of the basin is required.

3.3. Water storage results

Water storage reservoirs are required to maintain the water flow in the river during the dry period and allow the use of the waterway throughout the year. Analyzing the topography of the basins at 300 km from the interconnection of the different basins and 50 km from the waterway shows no potential for the creation of conventional reservoirs within the waterway. This is because the topography of the interconnection between the sedimentary basins has a flat topography. The construction of a conventional reservoir would require a large amount of land to store little water due to the low reservoir altitude variation. This would result in a large environmental impact and evaporation rates, particularly during the dry period (J. Hunt et al., 2018).

Even though there is no potential for the construction of conventional reservoir dams along the waterway, there are good locations for storing water parallel to the river in seasonal pumped hydropower storage reservoirs (SPHS). SPHS plants consist of two reservoirs, a lower and an upper reservoir connected by a pump/turbine and a tunnel (Fig. 8). For the case of the SWAS, the lower reservoir consists of a run-of-the-river reservoir formed by a small head waterway lock of around 15–30 m. It is meant to maintain the water level high enough so that river water can be pumped to an upper reservoir. The upper reservoir should have a large storage capacity to take up a large part of the water from the main river/waterway during the wet period. The water is then released during the dry period, and the lowest section of the dam will store water for use during droughts years. On average, a SPHS plant would require around 100 times less flooded land to store the same amount of water than conventional dams surrounding the SAWS (J. Hunt et al., 2018).

The region connecting the Orinoco and Amazon basins has a dry period from December to May, while the dry period in the region connecting the Amazon and La Plata is between June and September. As a result, seasonal water storage is needed to supplement the water level in the waterway and allow it to operate year-round.

Fig. 9 a-f illustrates three proposed SPHS plants for storing energy and water: two for the Amazon-La Plata and one for the Orinoco-Amazon interconnection. Table 2 presents the details of these prospective projects. The cost estimation of the proposed SPHS plants was estimated with the tool developed by the authors (J. Hunt et al., 2020). The proposed SPHS plants, as well as storing water for the operation of the SAWS, would regulate the flow of the Guaporé, Madeira, Negro and Orinoco rivers. This would increase the viability of constructing low-head, low-impact hybrid locks/hydroelectric plants (run-of-the-river stations). Even though the observed storage capacity of the proposed reservoirs is beneficial to maintaining a high river level during drought years, it would certainly not be enough to store the water resulting from flood events in the basin. Particularly the Tama Tama SPHS plant, as it only stores 1.3% of the river flow.

Given that the operation of the waterway with this large water level variation is challenging, locks are proposed to minimize the impact of water level variation. The locks could be built together with low-impact low-head hydropower plants. An example of such a dam is the Moveable Hydro-Electric Power Plant (HEPP), as presented in Fig. 9 (g) (Hunt et al., 2018). These dams have small heads, and the flooded area is minimal, as the maximum level of the reservoir is a few meters higher than the original river level during the wet period. The dam should be designed so that fish can pass through during the wet period without difficulty, as the dam's head is small. During the dry period, fish could cross through the waterway locks. Research is needed to confirm these expectations and determine whether new problems for flora and fauna would be created and, if so, find appropriate remedies. These hydropower plants have a high-capacity factor of around 70%. Another aspect that makes this technology potentially interesting for the region is the reduced on-site construction work involved. The dam's equipment can be produced far from the region and assembled in the river. This

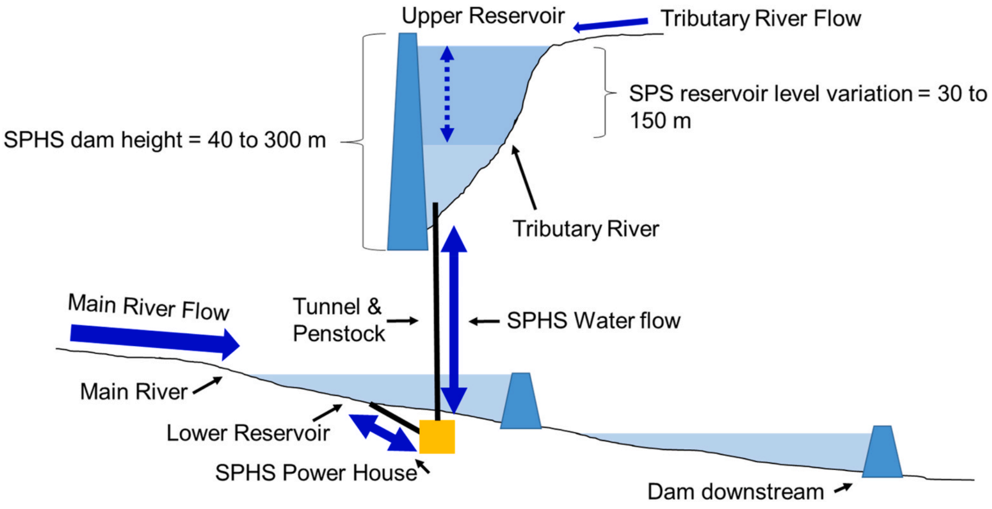


Fig. 8. Diagram of a seasonal pumped-hydro storage plant (J. D. Hunt et al., 2020).

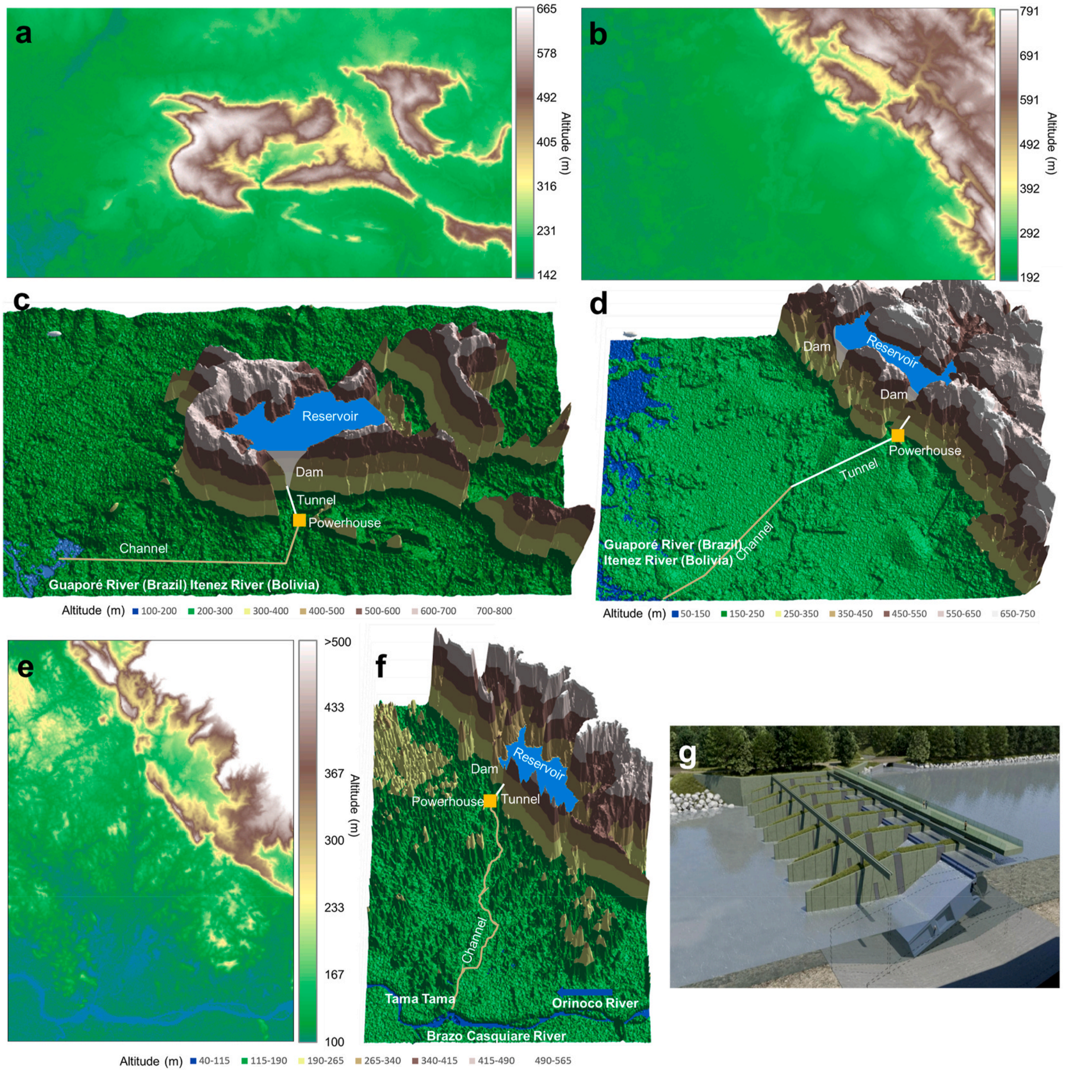


Fig. 9. Illustrations of alternative solutions that could be potentially integrated with the proposed waterway system. (a–b), proposed seasonal pumped-hydro storage plants (SPHS). Two were proposed for the Amazon-Plata interconnection San Simon SPHS and (c–d) Serra da Borda SPHP, and one in the Orinoco-Amazon interconnection (e–f) Tama Tama SPHS. (g) Proposal for Moveable Hydro-Electric Power Plant (HEPP) for the construction of the locks and to harness hydropower with low impact (EU - LIFE and E-Werk Mittelbaden and Hydro-Energie Roth GmbH, 2012) (locks are not shown in the illustration). Apart from Fig. 9 (g), the authors created all figures.

Table 2
Details of the proposed reservoirs to regulate the waterways flow. The table was created by the authors.

SPHP Project Name	Country	Dam height and level variation (meters)	Water storage (km^3)	River Discharge (km^3/s.y)	Channel/ Tunnel Length (km)	Avg. gen. head (m)	Flow to fill up reservoir (m^3/s)	Energy Storage (TWh)	Land use (km^2)	Energy storage cost ($/MWh)	Energy storage cost ($/GW)
San Simon	Bolivia	275/200	4.2	21.4	30/2	290	264	3.3	29	12	0.9
Serra da Borda	Brazil	233/200	2.3	4.5	25/5	305	144	1.9	18	15	1.1
Tama Tama	Venezuela	130/100	1.6	125.3	25/2	130	72	0.5	30.5	17	1.3

considerably reduces the environmental impacts associated with dam construction work.

4. Discussion

In the proposed integration, all South American countries, except Chile, could benefit from the interconnection of river basins. The country that would benefit the most is possibly Bolivia due to its lack of a coastal border. Currently, most Bolivian trade goes through Pacific Ocean ports and must cross the Andes mountains. By interconnecting the country with modern waterways, the country could be substantially benefited.

Possible sustainable development projects that could be implemented in integration with the waterway are presented in Table 3. These

Table 3
Sustainable activities to be developed around the waterways. Table created by the authors.

Sustainable Activities	Details	Examples of products
Sustainable natural extraction	Extraction of natural products from the forest without cutting down the forest.	Brazil Nut, Acai, Babassu (Florestas Brasileiras S.A., 2019)
Sustainable biomedical and biomaterial research and extraction	Research on using of natural elements to produce high-value products.	Medicine, cosmetics, high value-products
Sustainable fishery	Controlled extraction of fish which allows for maintaining a balanced aquatic ecosystem.	Fish
Sustainable tourism	Use the waterway as a touristic attraction with minimum impact on the environment and the river.	Tourism (Paulauskas et al., 2018)
Sustainable human settlement	Development of townships integrated with the forest with minimum impact on the environment and the river.	Controlled low-impact urban development
Sustainable flood control	Reducing the impact of flooding in the basins.	Control floods (Rose and Walker, 2014)
Sustainable water storage	Reduces the impact of droughts in the basins.	Water supply (Rose and Walker, 2014)
Sustainable regional development	Development of a regional economy focuses on the activities mentioned in this table with minimum impact on the forest and river system.	Sustainable regional economy
Sustainable mining extraction	Extraction of minerals with low impact on the forest or sedimentation of the river and tight control on deforestation.	Iron, Nickel, Lithium, Uranium
Sustainable oil and gas extraction	Extraction of oil and gas with minimum impact on the forest and river system.	Oil and gas
Sustainable hydropower development	Development of hydropower projects with minimum impact on the forest and river system.	Electricity
Intercontinental transportation	Transport of goods and services between countries within South America.	Transport network
Agroforestry	Many crops can be combined with the forest or grown under de forest due to their tolerance to shading (Ricketts et al., 2004).	Coffee, cocoa, guarana, cupuaçú, açaí.
Water transposition	Transpose water from one basin to the other to increase water distribution within the continent (Hunt and Leal Filho, 2018).	Food and biofuels
Sustainable selective logging	Selective logging is capable of sustaining natural ecosystems while permitting repeated harvests of high-value timber (Putz et al., 2008).	Certified sustainable timber
Hydrogen based economy	The preplacement of diesel with hydrogen from the ships will substantially reduce the pollution caused in the rivers. If hydrogen leaks it will rapidly escape to the upper atmosphere.	Eco-friendly ships and airships used for cargo transportation

activities would require advanced planning and involve auctions to investors committed to the sustainable use of the region's natural resources. Mismanagement and deviation from planned use would be subject to stiff fines and legal prosecution. All economic activity would only have access to the external market via the waterways and airships (as proposed in the following section). No road access would be allowed in critical protected areas to reduce the potential for deforestation.

For future work, it is important to run hydrological models for the Plata and Orinoco River basins to estimate the water level variation. This data will then be used to estimate the requirements for building locks so that the waterway can be utilized even during drought years. A detailed analysis is needed to estimate the potential carbon emissions from the waterway and to compare this output with land-based transportation. Regional water conflicts, threats and challenges between different countries, states, municipalities and other stakeholders should be explored in more detail Baigún and Minotti (2021).

4.1. South American waterway sustainable framework

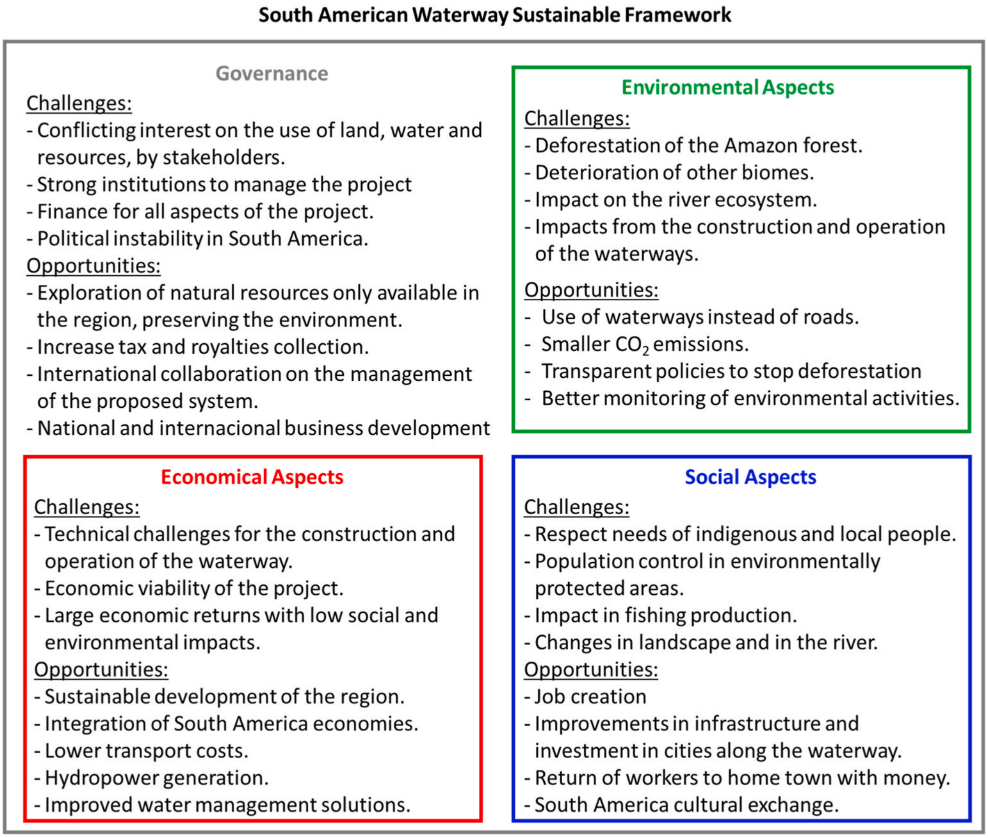
The proposed waterway has several challenges and opportunities that must be considered to analyze its viability. A sustainable development framework is proposed to analyze if the project makes sense as a whole and to provide possible solutions for the challenges faced by the waterway (Fig. 10). This framework is divided into four main aspects: Governance, Economic, Environmental, and Social. Governance is the principal aspect of the framework and is liable for the other three aspects. Appropriate governance should consider all the issues involving the project and implement it in the best possible way. Fig. 10 presents the most relevant challenges and opportunities for each of the four aspects. Due to the broad scope of this project, this paper only addresses partially the "Technical challenges for the construction and operation of the waterway" in the economic aspect, and the "Use of waterways instead of roads" in the environmental aspect. The other aspects should be addressed in future work for a comprehensive analysis of the SAWS.

4.2. Integrating waterways with the use of airships

The use of waterways cannot always reach communities in isolated areas, requiring other transport modes to complement them. Usually, road transportation has been used to integrate between river ports and remote terrestrial areas. However, the use of airships has been gaining momentum worldwide as a possible viable alternative in some market niches. It could be used, for example, in the transportation of goods produced in the forest and transported to the rivers connected to the waterways available to supply either the domestic market or export demands (Fig. 11). The advantage of using airships is the minimum impact of the transportation system in the forest (Hunt et al., 2019). This would allow the design of sustainable production systems that can only be accessed by airships, without the need for a road network, which could potentially lead to further deforestation of the Amazon Forest and other biomes, while also requiring large investment cost to develop and maintain the road system. Brazil is already developing airships to support the Amazon region's sustainable development (Piesing, 2017).

5. Conclusions

South America has been exporting its natural resources to developed countries for many years. On the other hand, many of the manufactured goods are imported. This is one of the reasons for the lack of growth and development in its hinterland and the development along the coast (Gioia, 1987). Trade between the nations in the area is small. A shared history, including the struggle for independence from Spain and Portugal, are at the root of this imbalanced expansion. Strategies to accomplish social and economic growth currently share similarities. This motivates citizens and the governments of South American nations to search for a shared future. The development of the hinterland will be a



South American Waterway Sustainable Framework

Governance

Challenges:
- Conflicting interest on the use of land, water and resources, by stakeholders.
- Strong institutions to manage the project
- Finance for all aspects of the project.
- Political instability in South America.

Opportunities:
- Exploration of natural resources only available in the region, preserving the environment.
- Increase tax and royalties collection.
- International collaboration on the management of the proposed system.
- National and internacional business development

Environmental Aspects

Challenges:
- Deforestation of the Amazon forest.
- Deterioration of other biomes.
- Impact on the river ecosystem.
- Impacts from the construction and operation of the waterways.

Opportunities:
- Use of waterways instead of roads.
- Smaller CO_2 emissions.
- Transparent policies to stop deforestation
- Better monitoring of environmental activities.

Economical Aspects

Challenges:
- Technical challenges for the construction and operation of the waterway.
- Economic viability of the project.
- Large economic returns with low social and environmental impacts.

Opportunities:
- Sustainable development of the region.
- Integration of South America economies.
- Lower transport costs.
- Hydropower generation.
- Improved water management solutions.

Social Aspects

Challenges:
- Respect needs of indigenous and local people.
- Population control in environmentally protected areas.
- Impact in fishing production.
- Changes in landscape and in the river.

Opportunities:
- Job creation
- Improvements in infrastructure and investment in cities along the waterway.
- Return of workers to home town with money.
- South America cultural exchange.

Fig. 10. South American Waterway Sustainable Framework. Figure created by the authors.

Fig. 11. Integration between airships and the proposed South American Waterway. Figure created by the authors.

part of this future, as well as the quick spread of regional industry and commerce.

The South American Waterway System will result in a 51.200 km waterway, including the existing waterways in Venezuela, Colombia, Peru, Ecuador, Bolivia, Paraguay, Brazil, Argentina and Uruguay. This will make it possible for all South American nations to have a high level of commercial integration with both current and emerging means of transportation, by incorporating the continent's hinterland and its carefully exploited resources into the process of economic and social growth. The SWAS will enable the assimilation of the labor force that is currently unemployed, integrating the three low population areas of the continent (Patagonia, the Pantanal, and Amazonia) spatially, economically, socially, and culturally. A land that is currently perceived as a broken structure with social and economic systems that are completely isolated.

At this point, economic activity is not the initial cause of the development of the SWAS but rather its subsequent result. The major gains will come from the external economies produced as a result of concerted efforts from the entire South American continent. We might claim that this initiative hints at economic expansion with a focus on raising the incomes of the underprivileged, causing society to become more concerned and cautious about environmental destruction.

It is important to remember that the SWAS is situated in the largest natural area on the planet, where around 20% of the world's freshwater is produced. Additionally, it is crucial to keep in mind that some ecosystems, like the soils in the Amazon, are extremely fragile, emphasizing the necessity of treating them rationally. This suggests that the potential for agricultural exploitation should be strictly constrained. Naturally, extra attention will need to be paid to environmental issues. We need to be certain that the nations involved in this plan would adequately safeguard other factors, including the preservation of cultural property, the wealth of genetic diversity, and the welfare of future generations. We believe that South America's current and varied issues, such as forest logging or shanty settlements in urban areas, will start to be seriously considered and treated with the help of the SWAS. The comparison of deforestation surrounding existing road and waterway infrastructure in the Amazon region indicates that deforestation around the future SWAS might not be difficult to control.

To ensure that the economic, environmental and social aspects of the proposed waterway are considered, an initial South America Waterway Sustainable Framework has been proposed. The main aspects analyzed in this paper were the possibility of using the SAWS to improve the monitoring of deforestation and other illegal activities in the region, as all goods would have to pass through only a few choke points in the waterways, ultimately reducing the deforestation of the Amazon forest. It also proposes solutions to the seasonal water availability, one with reservoirs built parallel to the river and another using the groundwater storage capacity within the sedimentary basin. If this waterway system is to be considered in the future, the proposed framework needs to be substantially expanded and detailed, and a cohesive and ambitious regional development plan shall be developed. The SAWS has a large potential for sustainable development in South America at the same time, it can reduce the deforestation of the Amazon forest.

Data availability

Data will be made available on request.

Acknowledgments

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